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5.1 GENERAL

Diesel engines play a vital role in automobiles and agricultural sectors [1, 2]. During combustion the fuel is injected into the combustion chamber through the fuel injector which takes place at the end of compression. Diesel engines are manufactured for using diesel as a fuel to release the energy, but in these research methyl esters of rubber seed oil is utilized as a fuel for combustion. During the tests with Rubber seed oil biodiesel fuel, the engine was started with diesel until it warmed up. Then the fuel was switched to Rubber seed oil biodiesel. After finishing the tests with Rubber seed oil biodiesel, the fuel was always switched back to diesel and the engine is allowed to run with diesel for few minutes to remove the methyl ester layers present in the engine.

Cyclic variations of the cylinder pressure can cause large variation in cylinder pressure level [3, 4, 5]. The data acquisition system utilized in the present investigation is a computer based system in which the signals can be monitored in the screen. The fluctuations seen on the screen is the average of 10 consecutive cycles. During experimental studies the fluctuation of speed can be varied of ± 5 rpm, and the speed can be monitored by using analog system.

5.2 COMBUSTION AND EMISSION CHARACTERISTICS OF BLENDS OF BIODIESEL AT CR= 16

The results obtained from the experimental investigation of the combustion, performance and emission parameters using B20, B40, B60, B100 & Diesel as fuels are presented and discussed in this section. The results are also compared with diesel fuel operation for different Compression Ratios.
5.2.1 Brake Thermal Efficiency

The brake thermal efficiency of the engine is given by

\[ \text{BTE} = \frac{3600}{(\text{CV} \times \text{BSFC})} \]

Where,

\[ \text{BTE} = \text{Brake thermal efficiency, } \% \]
\[ \text{CV} = \text{Calorific value of fuel used, } \text{kJ/kg} \]
\[ \text{BSFC} = \text{Brake specific fuel consumption, } \text{g/kWh} \]

Fig.5.1 Variation of brake thermal efficiency with brake power

The variation of brake thermal efficiency with respect to CR-16 for different fuels considered in the present analysis is presented in Fig.5.1. From the graph it can be analyzed that thermal efficiency increases with increase in load due to increase in power and reduction in heat loss.

From the observation of the results, it has been concluded that the brake thermal efficiency of the blend B20 is slightly higher than that of the standard diesel at CR-16.
When the methyl ester of rubber seed oil is mixed with diesel, the molecules present in the methyl ester contains oxygen compounds which makes the combustion faster and it leads to complete combustion. Even though the biodiesel has some lubricity characteristics which makes the reaction faster at the time of combustion. The maximum brake thermal efficiency was 35% and 33% for B20 and B40 as compared to 32% for Diesel. By analyzing the graph when the biodiesel blend gets increases, the thermal efficiency starts decreasing due to reduction in heating value [6]. This is mainly due to longer ignition delay result in late burning which leads to a reduction in thermal efficiency.

5.2.2 Specific fuel Consumption

The fuel consumption of an engine is measured by determining the time required for consumption of a given volume of fuel [7, 8]. The time taken by the engine to consume the fuel is measured on its volume basis. The test engine has the provision for measuring both diesel and biodiesel. These two fuels are stored in separate tanks in the engine, initially the engine is fuelled with diesel and then it is switched over to biodiesel. When the stable operating conditions have been achieved the engine is allowed to run at different operating conditions.

The variation in BSFC with load for different fuels is presented in Fig.5.2. From the figure it can be noticed that the specific fuel consumption increases with increase in blend at low load and decreases with decrease in blend at high load may be due to the increase in viscosity of the blend.
The mean BSFC for the blends was higher than that of pure diesel and it is to be noted as for every 20% additional blending of biodiesel in diesel. Increase in density of methyl esters causes higher injection pressure to inject the fuel in the combustion chamber. The lowest BSFCs are 0.22, 0.25, 0.28, 0.29 and 0.32 kg/kWh for diesel B20, B40, B60 and B100 respectively. The fuel consumption of any compression ignition engines depends on the characteristics such as volumetric fuel injection system, density, viscosity and lower heating value.

5.2.3 Peak Cylinder Pressure

In a compression ignition engine, the peak cylinder pressure depends on the burning of fuel inside the combustion chamber at the time of combustion. The variation of cylinder pressure with biodiesel and its blends in comparison with diesel fuel for compression ratio 16 is shown in Fig.5.3.
Fig. 5.3 Variation of cylinder pressure with brake power

It is noticed from the figure that the peak pressure for diesel increases from 47.5 bar to 70 bar for diesel from no load to full load and the cylinder pressure gets decreases when the biodiesel blends gets increases.

The maximum pressure of a diesel engine supports the combustion at the initial period which mixes in the premixed combustion period. The premixed combustion is dependent on the delay period and the mixture preparation [9, 10]. From the statistical approach it can be noticed that ignition delay takes place when the engine is fuelled with methyl esters and less delay period is seen when the engine undergoes combustion with diesel.

5.2.4 Combustion Duration

Increase in pressure rise reduces the combustion duration. When the piston reaches the top dead center, the maximum pressure is achieved for a long duration of time which gives the power stroke.
Fig. 5.4. shows the variation of combustion duration with brake power for different blends of biodiesel. When the engine operates at lean or rich mixture the rate of combustion can be increased and the reduction in flame propagation can be seen due to deficiency in oxygen compounds [11, 12]. The combustion duration is higher for increase in brake power for a compression ratio of 16. The highest combustion duration is noted as 105° crank angle at full load when the engine is fuelled with biodiesel and the lowest is about 74° crank angle for diesel. It can be observed that the combustion duration decreases with decrease in blend of biodiesel, which indicates faster heat release and leads to high thermal efficiency.

5.2.5 Exhaust Gas Temperature

The variation of Exhaust Gas Temperature with respect to brake power for blends of biodiesel when running at compression ratio 16:1 is presented in Fig5.5.
Normally exhaust gas temperature increases with increase in load for diesel and blends of biodiesel. The maximum temperature has been achieved for diesel fuel when it undergoes combustion from no load to high load and the temperature is recorded as 137°C at no load to 310°C at full load. When the engine is loaded in steps it consumes more amount of fuel to produce more power depending on the load. The pure methyl esters of rubber seed oil gives low exhaust temperature when compared with the diesel due to its low heating value and more oxygen compounds present in the biodiesel make the combustion complete.

The exhaust gas temperature was lower for blends of biodiesel than Diesel. The highest temperature recorded as 296°C for Diesel and for biodiesel it is recorded as 284°C. The reason being the lower calorific value of blended fuels compared to diesel and the lower temperature at the end of compression. Also, biodiesel is partially oxidized
while burning, and it has lower temperature which results in reduced exhaust gas temperature.

5.2.6 Pressure - Crank angle Diagram

The cylinder pressure versus crank angle obtained at peak power output for full load is shown in Fig.5.6. The methyl esters of rubber seed oil gives longer ignition delay than the ordinary diesel fuel which starts the combustion later. The ignition delay for biodiesel is due to its lower content of volatile compound in comparison with the diesel. More energy is released in the latter part of the expansion process which will reduce the thermal efficiency and increase the exhaust gas temperature. When knock occurs high frequency pressure fluctuations are observed whose amplitude decays with time [13, 14]. It occurs late in the burning process and the amplitude of the pressure fluctuation is small. The initial amplitude of the pressure fluctuation is much longer thereby causing a shock wave to propagate away from the end gas region across the combustion chamber.

![P-Tetha Diagram](image)

Fig.5.6 Variation of Cylinder pressure with Crank angle
It can be noticed that the cylinder pressure is reduced when the flow rate is increased. It can be seen that Diesel has low peak pressure than rubber seed oil methyl ester when the engine is running at a compression ratio of 16:1. The maximum peak pressure is about 72 bar for biodiesel at full load conditions and the lowest peak pressure is about 62 bar for diesel. The premixed combustion is dependent on the delay period and the mixture preparation. Higher cetane number has the capability to reduce the ignition delay when fuel is send inside the engine cylinder which leads to the formation of increase in smoke at the engine exhaust.

5.2.7 Heat Release Rate

The combustion heat release profiles for Diesel & biodiesel for CR=16 at full load is shown in Fig 5.7. The profiles produces different ignition delays, longer delays allow more fuel to mix with in the combustible limits during the delay.

![Heat Release Vs Theta](image)

**Fig.5.7 Variation of Heat Release with Crank angle**
It can be observed that the heat release rate for diesel is low when compared to biodiesel with respect to CR 16. In methyl esters of rubber seed oil higher heat release is observed, it can occur due to the premixed combustion phenomena, and when comparing it is higher than the diesel fuel. It may result due to the high viscosity of biodiesel which leads to reduced fuel air mixing and make the combustion earlier.

5.2.8 Smoke

The smoke from the Diesel engine using methyl esters of rubber seed oil and its blends with Diesel for a compression ratio of 16:1 is shown in Fig.5.8. When the combustion takes place inside the engine cylinder, the smoke level increases due to the increase in fuel for diesel and blends of methyl esters. When the load increases more amount of fuel is essential to produce more power, at this juncture the injected fuel won’t find the sufficient time for complete combustion, in which some of the partially burned fuel goes through the exhaust as smoke. It can be noticed that blends of methyl esters generates more smoke when comparing with the diesel fuel.

![Fig.5.8 Variation of Smoke with brake power](image-url)
The recorded values of intensity of smoke generated for blends B20 to B100 were 16% and 27% at no load and for maximum load it is about 50% to 72% respectively. The smoke level is higher with rubber seed oil methyl ester as compared to diesel, due to its improper atomization of fuel mixture. Normally in diesel engine smoke formation generally occurs in the rich zone at high temperatures [15].

5.2.9 Carbon monoxide (CO)

Incomplete combustion of carbon leads to CO formation. CO is a toxic combustion product. In the presence of sufficient oxygen, CO is converted into CO₂. The formation of CO takes place when the oxygen for combustion is insufficient to form CO₂. Initially at no load condition, less temperature is recorded inside the engine cylinder, but the temperature of the engine cylinder is increased at higher loads due to consumption of more amount of fuel inside the cylinder.

![Fig.5.9 Variation of Carbon monoxide with brake power](image-url)
Formation of CO in the case of rich mixture mechanism seems to be primarily determined by the rate at which the fuel-rich zones within the fuel jets are fed with air. Both mechanisms involve chemical kinetics and hence are expected to be temperature sensitive [16]. Fig.5.9 shows the graphical representation of carbon monoxide emission for blends of methyl esters of rubber seed oil and diesel fuel when the engine is running at a constant speed at different loading. There is no much variation for Diesel and B20, due to similar properties of fuels. When the load of the engine increases the fuel air ratio is reduced which shoots the carbon monoxide higher. The maximum value of CO for rubber seed oil methyl ester is found to be 0.094% under full load conditions and the minimum value for diesel is found to be 0.052%. It was observed that during the initial period when the engine is running at zero load the temperature inside the cylinder is very low, and when it is loaded in steps to generate maximum power, more amount of fuel is injected in to the engine cylinder which leads to the formations of emission.

5.2.10 Unburned Hydrocarbons (HC)

Exhaust gases leaving the combustion chamber of an engine contains more amount of hydrocarbon components. This may result due to improper burning of fuels; due to increase in molecular weight of diesel fuel when it undergoes combustion the temperature gets increases and results in higher emissions.
Fig. 5.10 shows the variation of hydrocarbon emission with different fuels when the engine is running at a compression ratio of 16:1. The hydrocarbon level increases with increase in load for all the fuels. For rubber seed oil methyl ester the HC emissions are lower than that of diesel fuel. This may be due to the fact that pure biodiesel contains more oxygen and this leads to better combustion.

The HC emission for diesel fuel differs from 22ppm at zero load to 67ppm at peak load and for pure biodiesel it ranges from 16ppm at zero load to 40ppm at maximum load. As the ignition delay period increases the fuel mixture loses its efficiency and tries to become leaner than the required combustion. Often this may occur at the periphery of the fuel spray, where vaporized fuel may be stripped off and carried away by the swirling air [17]. This leads to the reduction in HC emission for pure biodiesel than diesel.
5.2.11 Oxides of Nitrogen (NOₓ)

Nitric oxide emission is one of the major pollutants emerged from the engine exhaust when it undergoes combustion. It causes mainly due to increase in temperature during the combustion period. Normally NOₓ is measured in parts per million. Fig.5.11 shows the graphical representation for blends of methyl esters when the engines is allowed to run at a compression ratio of 16:1.

The nitric oxide emission from the engine exhaust for the blends of methyl esters of rubber seed oil varies from 235 to 674ppm and for diesel it varies about 222 to 475ppm. From the graph it can be concluded that increase in proportion of biodiesel with diesel increases the nitric oxide emission.

![Graph showing variation of NOₓ with brake power at CR=16](image-url)

**Fig.5.11 Variation of Oxides of Nitrogen with brake power**
Methyl esters are oxygenated fuels; increase in oxygen content increases the exhaust gas temperature at the engine exhaust which leads to the formation of NOx. Normally increase in load increases the air-fuel ratio, which increases the temperature in the engine cylinder leads to generate higher nitric oxide emissions.

5.3 COMBUSTION AND EMISSION CHARACTERISTICS OF BLENDS OF BIODIESEL AT CR= 18

5.3.1 Brake Thermal Efficiency

The variation of brake thermal efficiency with respect to brake power for different blends of methyl esters of rubber seed oil when the engine is running at a compression ratios of 18:1 is shown in Fig.5.12. Normally thermal efficiency increases with increase in load for all fuels, but when comparing the maximum efficiency at full load for blends of biodiesel and diesel, methyl ester blend B40 gives the maximum efficiency of about 36%. This may cause due to the increase in percentage of oxygen in the biodiesel, which can go for complete combustion.
The blend B100 gives lower efficiency than the diesel fuel and it is recorded as 31%, which may cause due to the increase in viscosity and high density of the fuel. When comparing the efficiencies for the different blends it can be noticed that at full load conditions the efficiencies varies in a slight manner but major difference is noticed for the blends B40 and B100.

5.3.2 Specific fuel Consumption

The variation of specific fuel consumption with respect to brake power for different fuels for a compression ratio of 18 is considered for the present analysis is presented in Fig.5.13. From the graphical representation it can be noticed that the specific fuel consumption increases with increase in blend at low load and decreases with decrease in blend at high load, be due to the increase in viscosity of the blend. When low percentage of methyl ester is added with the diesel, the brake specific fuel consumption gets lowered and it matches close to diesel fuel.

![Fig.5.13 Variation of Specific fuel consumption with brake power](image-url)
From the figure it can be noticed that the brake specific fuel consumption for the blends B20, B40, B60, B100 and Diesel is having a value of 0.24, 0.26, 0.27, 0.29 & 0.31 kg/kWh. By seeing the values it can be noticed that increase in viscosity of the blend the brake specific fuel consumption increases at maximum load conditions. The heating value of the fuel decreases when blends of methyl ester get increases, so that the engine is in a position to consume more amount of fuel to generate the power output.

5.3.3 Peak Cylinder Pressure

The cylinder pressure increases as combustion of the fuel-air mixture occurs. Fig. 5.14 shows the variation of in-cylinder pressure for Diesel, B20, B40, B60 & B100 with respect to crank position from no load to full load for compression ratio 18.

![Variation of Cylinder pressure with brake power](image)

**Fig.5.14 Variation of Cylinder pressure with brake power**

The peak value of pressure depends on the fuel properties, combustion process and the engine load. As shown in figure the peak pressure of all the tested fuels increases with load, this may be due to more amount of fuel gets burned and the consequent release
of heat at higher loads. The peak pressure varies from 48bar at no load to 67bar at full load for diesel and the cylinder pressure gets reduced when it is blended with biodiesel.

It may be noticed from the figure that for a B100 blend the cylinder pressure drastically reduced from 42 bar to 54 bar. Normally in diesel engines the rise in pressure depends on the combustion phenomena in which it may vary depending on the fuel injection rate in the engine cylinder. This is because, ignition delay increases and longer delay leads to sufficiently late ignition occurring in the expansion process consequently leads to incomplete combustion and lower fuel conversion efficiency and power output [18].

### 5.3.4 Combustion Duration

Combustion duration mainly depends on the mixture of the fuel air ratio when the engine is operating in lean or rich mixture. Normally in lean mixture more amount of oxygen is present, so the fuel has a tendency to go for complete combustion when compared with the rich mixture. When the duration of combustion increases misfiring takes place inside the engine cylinder, which leads to the reduction in specific fuel consumption and this may leads to increase in thermal efficiency.

The variation of combustion duration with brake power for different blends of biodiesel is compared with diesel for compression ratio of 18 is indicated in Fig.5.15. The peak value of combustion duration depends on the fuel properties, combustion process and the engine load. The combustion duration for B60 & B100 is almost same and the highest value is noted as 89° & 94° CA and the lowest value for diesel is about 62° CA when the engine is running at full load conditions.
5.3.5 Exhaust Gas Temperature

Fig. 5.16 shows the variation of Exhaust Gas Temperature with brake power for the tested fuels when running at compression ratio of 18:1.
The exhaust gas temperature varies from 155°C at no load to 295°C at full load for diesel fuel, from 145°C to 290°C for B20 and from 150°C to 274°C for rubber seed oil methyl ester. It can be seen from the figure that exhaust gas temperature lines for various fuel blends are closer to each other in a narrow band. The reason for lower exhaust gas temperature for biodiesel blends is due to its increase in viscosity, the fuel mixture cannot atomize in to fine spray in the combustion chamber, there by releasing lesser amount of heat [19].

5.3.6 Pressure - Crank angle Diagram

Fig.5.17 indicates the cylinder pressure with crank angle for different blends of biodiesel at maximum load conditions when the engine is running at a compression ratio of 18:1. Normally cylinder pressures are higher for blends of methyl esters of rubber seed oil when the engine is running at low loads. During peak loads the pressure fluctuations are noticed from the graph and it is similar for methyl ester blends. The peak cylinder pressure for biodiesel is 72 bar and for diesel is 63 bar at full load conditions.
Due to longer delays the combustion starts later for diesel than biodiesel during low loads. The cylinder pressure makes a value lower and it moves far from top dead centre during the expansion stroke. During high load the cylinder pressure makes near the crank angle for all the fuels. Increase in load reduces the delay period and it rises more quickly than the premixed burning phase.

5.3.7 Heat Release Rate

The variation of heat release rate with respect to crank angle for blends of biodiesel at compression ratio 18 is shown in Fig.5.18. Heat release rate is not a fundamental property of fuel, but the effective heat of combustion is a measure of how much energy is released when a unit mass of material is oxidized. Normally complete combustion can be mentioned as the release of energy takes place inside the engine cylinder when the fuel undergoes chemical reaction leaving no fuel inside the engine cylinder.

![Heat Release Vs Theta](image)

**Fig.5.18** Variation of Heat Release with Crank angle
The diagram represents that when the engine is running with twenty percentage blends of biodiesel reduced in ignition delay can be found when it is compared with diesel. From the graph it can be noticed that the heat release curves fluctuates steeply during peak loads and it comes to the normal position when the engine is running at no load. This may occur due to the increase in density of the rubber seed oil methyl ester which cannot go for proper atomization when the fuel is sprayed inside the combustion chamber. Due to incomplete combustion the exhaust temperature gets increased and finally it leads to increase in emission.

5.3.8 Smoke

Fig.5.19 depicts the variation of smoke density with respect to brake load for blends of biodiesel when running under compression ratio 18:1 is discussed below. It may be observed that smoke decreases with decrease in biodiesel blends. This is due to uniform mixture present inside the cylinder which leads to complete combustion and higher heat release rate in the premixed combustion phase.

![Fig.5.19 Variation of Smoke with brake power](image_url)
From the graph it can be noticed that when the percentage of methyl ester blend gets increases, due to its incomplete combustion, smoke increases when the engine is running at full load conditions. The maximum value of smoke for rubber seed oil methyl ester is about 78%, and for diesel it is 59%. The lowest smoke emission can be seen for the blend B40, it may results due to the complete combustion of the fuel by the presence of oxygen in the biodiesel. The aromatic content in the blend is increased with constant cetane number, particulate emission increases at high load [20, 21]. Increase in smoke can be seen for higher blends, this may cause due to incomplete combustion of rubber seed oil methyl esters.

5.3.9 Carbon monoxide (CO)

The variation of carbon monoxide emission with engine loading for different fuels when running at a compression ratio of 18:1 is shown in Fig 5.20.
The carbon monoxide emission varies from 0.018% at no load to 0.049% at full load for diesel fuel, for rubber seed oil methyl ester it varies from 0.024% at no load to 0.085% at full load respectively. It can be seen that when the blends of biodiesel is increased the carbon monoxide emission also increases drastically. It is found that for B20 & B40 the CO emission reduces than the 100% biodiesel, this is due to the fact that oxygen present in the blends may lead to complete combustion thereby lowering CO emissions.

The enrichment of oxygen owing to rubber seed oil addition as increasing the proportion of oxygen will not only decrease the incomplete combustion products such as CO especially during the diffusive combustion process, but also promote further oxidation of CO during the engine expansion and exhaust process. The study reveals that operating on the oxygenated fuels would reduce the engine incomplete combustion products as a result of oxygen enrichment [22, 23].

5.3.10 Unburned Hydrocarbon (HC)

Emission characteristics vary depending on the combustion phenomena of an engine. When the fuel injected in to the engine cylinder is not mixed properly with air and during combustion it leads to higher hydro carbon emissions. The variation of hydrocarbon emission level with break power for blends of biodiesel is depicted in Fig.5.21 when the engine is running at a compression ratio of 18:1. From the graph it can be noticed that the hydro carbon emissions for Diesel, B20, B40, B60 & B100 are 62, 59, 54, 48 & 43ppm respectively. By analyzing the emission results it can be concluded that increase in rubber seed oil methyl ester blend decreases the hydro carbon levels. It is one
of the fact that the oxygen concentration present in the biodiesel undergoes complete combustion thus reduces the hydrocarbon level in the engine exhaust timing.

![Graph showing variation of Hydrocarbon with brake power](image)

**Fig.5.21 Variation of Hydrocarbon with brake power**

The hydrocarbon emission also varies depending on the injection timing of the fuel. If the injection is advanced before its desired timings, longer delay occurs which leads to higher emissions of hydrocarbons in the exhaust of the engine.

### 5.3.11 Oxides of Nitrogen (NO\textsubscript{X})

The variation of NO\textsubscript{X} with brake power for diesel fuel and blends of biodiesel when running under a compression ratio of 18:1 is indicated in Fig.5.22. The NO\textsubscript{X} emission varies from 160ppm at low load to 440ppm at full load for diesel fuel, while for biodiesel it varies from 260ppm at low load to 660ppm at full load. The major cause for nitric oxide emission depends on the temperature occurs inside the engine cylinder during combustion and the presence of nitrogen present in the atmospheric air.
Due to increase in load more amount of fuel is injected in to the engine cylinder and when it undergoes combustion it releases more amount of temperature in the engine cylinder which leads to $\text{NO}_x$ formation. In the case of methyl esters of rubber seed oil, the viscosity of the biodiesel is higher than diesel which makes the combustion delay and leads to nitric oxide emission. The reason for higher $\text{NO}_x$ for the blends is due to higher peak temperature at the time of combustion in the engine cylinder.

5.4 COMBUSTION AND EMISSION CHARACTERISTICS OF BLENDS OF BIODIESEL AT CR= 20

5.4.1 Brake Thermal Efficiency

The variation of brake thermal efficiency (BTE) with respect to brake power for different fuels is shown in Fig.5.23. Due to increase in engine load the thermal efficiency increases and it attains the peak value and reduces slightly with further increase in load.
Fig. 5.23 Variation of Brake thermal efficiency with brake power

According to the addition of ROME content in the blend, the BTE initially increases until reaches a maximum value at B60 blend for a compression ratio of 20 and then decreases with decrease of the ROME content in blend. The maximum brake thermal efficiencies were obtained to be 36.35% and 35.80% for B60 and B100, respectively, which were higher than that of diesel (33.56%). When methyl esters of rubber seed oil is added with the diesel fuel, the density and viscosity of the fuel increases which reduces its calorific value and the reduction in efficiency can be achieved. But when the engine is running at higher compression ratios the presence of oxygen in methyl esters makes the combustion faster which leads to increase in efficiency for the blend B60 and B100. The reason for this is the biodiesel includes approximately 10% (in weight) oxygen that can be used in combustion, especially in the fuel rich zone [24].
5.4.2 Specific fuel Consumption

The variation of specific fuel consumption with respect to brake power for different fuels for a compression ratio of 20 is considered for the present analysis is presented in Fig.5.24. The specific fuel consumption of B20 blend is lower than that of all other blends at compression ratio 20. The reason may due to the presence of oxygen in the methyl ester under goes complete combustion.

From the graph it can be noticed that the specific fuel consumption values for Diesel, B20, B40, B60 & B100 are 0.23, 0.21, 0.25, 0.27 & 0.3 kg/kWh. Normally compression ratio and specific fuel consumption are proportional to each other. When the blends of biodiesel increases the heating value of the fuel get reduced and it makes the specific fuel consumption to increase [25, 26].
5.4.3 Peak Cylinder Pressure

In a diesel engine, the pressure of the cylinder depends upon the fuel burned during the premixed combustion phase [27]. The variation of rate of pressure rise with brake power for diesel and blends of biodiesel for a compression ratio of 20 is shown in Fig.5.25. It is observed that peak pressure rises for blends of biodiesel when the compression ratio increases. Maximum cylinder pressure has been achieved for B100 from 47 at no load to 68 bar at full load conditions.

![Fig.5.25 Variation of Cylinder pressure with brake power](image)

Biodiesel is an oxygenated fuel which have the capability to undergo complete combustion, leads to increase in pressure rise inside the engine cylinder. The trend of increase in peak pressure is due to increase in ignition delay with increase in RSOME increases the amount of fuel burnt in the premixed burning phase. Good atomization requires high nozzle opening pressure, optimum fuel viscosity and high cylinder air pressure at the time of nozzle opening. The rate of vaporization of the fuel depends on the
size of the droplets, distribution and the volatility of the fuel. The viscosity of biodiesel is slightly higher than diesel fuel. Higher nozzle opening pressure causes smaller droplets and higher rate of vaporization resulting in higher cylinder pressure.

5.4.4 Combustion Duration

Increase in pressure rise reduces the combustion duration. When the piston reaches the top dead center, the maximum pressure is achieved for a long duration of time which gives the power stroke. When the engine operates at lean or rich mixture the rate of combustion can be increased and the reduction in flame propagation can be seen due to deficiency in oxygen compounds.

![Variation of Combustion duration with brake power](image)

**Fig.5.26 Variation of Combustion duration with brake power**

The combustion duration for Diesel, B20, B40, B60 & B100 are to be noted as 102, 107, 120, 127 & 134°CA at full load conditions when the engine is running at a compression ratio of 20. It can be observed that the combustion duration decreases with
decrease in blend of biodiesel, which indicates faster heat release and leads to high thermal efficiency.

5.4.5 Exhaust Gas Temperature

The variation of exhaust gas temperature for different blends of biodiesel when running under a compression ratio of 20:1 is shown in Fig. 5.27. The exhaust gas temperature for the blends of methyl esters of rubber seed oil is greater than the diesel fuel due to increase in compression ratio may be due to incomplete combustion takes place inside the engine cylinder. The highest temperature obtained is 330°C for rubber seed oil methyl ester, whereas the temperature is only 270°C for diesel. The reason for the reduction in exhaust gas temperature at increased compression ratio is higher calorific value of diesel fuel as compared to blends of biodiesel [28, 29].

![Fig.5.27 Variation of Exhaust gas temperature with brake power](image-url)
5.4.6 Pressure - Crank angle Diagram

The variation of cylinder pressure with crank angle for different fuels when the engine is running at a compression ratio of 20:1 is shown in Fig.5.28. It may be seen that the ignition delays are longer with RSOME than diesel which can delay the start of combustion. More energy is released in the latter part of the expansion process which will reduce the thermal efficiency and increase the exhaust gas temperature. When knock occurs high frequency pressure fluctuations are observed whose amplitude decays with time. It occurs late in the burning process and the amplitude of the pressure fluctuation is small. The initial amplitude of the pressure fluctuation is much longer thereby causing a shock wave to propagate away from the end gas region across the combustion chamber.

![P-Theta Diagram](image)

**Fig.5.28 Variation of Cylinder pressure with Crank angle**

It is observed that peak pressure decreases with increase in compression ratio. At lower compression ratios, the peak cylinder pressure for diesel is higher than that for
blends of biodiesel. The highest cylinder pressure obtained is about 48 bar for biodiesel, at full load conditions the pressure amplitudes fluctuates and the pressure gets reduced.

5.4.7 Heat Release Rate

The variation of heat release rate with crank angle for Diesel & biodiesel at compression ratio 20:1 is indicated in Fig.5.29. The changes occur in the cylinder pressure and volume of the cylinder during the forward and backward motion of the piston leads to increase in heat release rate.

![Heat Release Vs Theta](image)

**Fig.5.29 Variation of Heat Release with Crank angle**

When the delay period occurs inside the engine cylinder, the heat loss occurs during the vaporizing of fuel inside the cylinder. Heat released during the premixed combustion is higher for blends of biodiesel than diesel due to longer ignition delay resulting from lower cetane number and higher latent heat of vaporization. It can be observed that the heat release rate for blends of biodiesel is higher compared to diesel fuel, due to longer ignition delay characteristics. Due to lower net calorific value of
biodiesel more fuel is necessary for the combustion process to meet the same power output. The peak heat release rate for B100 is 22 J/°CA, for diesel fuel is 16 J/°CA. The lowest value is noted for B60 is about 14 J/°CA. It can be observed that peak heat release rate increases as a function of longer ignition delay. This is due to greater amount of combustible fuel-air mixture formed during the ignition delay burning.

5.4.8 Smoke

Smoke is nothing but solid soot particles suspended in exhaust [30]. The smoke from the engine using B100 and its blends with diesel running on compression ratio 20:1 is shown in Fig.5.30.

![Figure 5.30 Variation of Smoke with brake power](image)

Normally smoke intensity increases when the load of the engine is increased for blends of methyl esters of rubber seed oil and diesel. The reason may be due to reduction in air fuel ratio when the engine undergoes combustion at higher loads. The average
smoke densities were 20%, 27%, 37%, 52%, 56% and 65% for diesel and 27%, 37%, 52%, 68%, 72% and 79% for B100 at 0%, 20%, 40%, 60%, 80% and 100% loads, respectively. The intensity of smoke shows a major difference between the pure biodiesel and diesel when the engine is running at higher loads may be due to the complete combustion of biodiesel at higher temperatures.

5.4.9 Carbon monoxide (CO)

The variation of carbon monoxide emissions with engine loading for different fuels when running at a compression ratio of 20:1 is shown in Fig.5.31. CO is a toxic combustion product. In the presence of sufficient oxygen, CO is converted into CO$_2$. The formation of CO takes place when the oxygen for combustion is insufficient to form CO$_2$. Initially at no load condition, cylinder temperatures might be too low, which increased with loading due to more fuel injected inside the cylinder.

![Fig.5.31 Variation of Carbon monoxide with brake power](image_url)
From the graph it can be seen that the carbon monoxide values for Diesel, B20, B40, B60 & B100 are 0.087, 0.092, 0.08, 0.073 & 0.068. By analyzing the values it can be seen that pure methyl esters of rubber seed oil gives lower carbon monoxide emission than the diesel fuel at full load conditions, this may occur due to the complete combustion takes place inside the engine cylinder.

5.4.10 Unburned Hydrocarbons (HC)

Hydrocarbon is an important parameter for determining the emission behavior of the engines. Fig.5.32 shows the variation of HC emission with break power for different blends when the engine is running at a compression ratio of 20:1. It is observed that at higher compression ratios the hydrocarbon emissions are higher. The effects of fuel viscosity, on the fuel spray quality are expected to produce some HC increase with vegetable oil fuels [31].

Fig.5.32 Variation of Hydrocarbon with brake power
It has been observed from the figure that there is no definite trend with biodiesel percentage increase in the blends. It shows that the hydrocarbon emission for the blend B40 is higher. It varies from 35ppm to 74ppm from no load to full load. The other blend Diesel, B20, B60 and B100 fuel produces lesser hydrocarbon emissions.

5.4.11 Oxides of Nitrogen (NO$_X$)

Fig.5.33 shows the variation of NO$_X$ emission with respect to brake power when running under a compression ratio of 20:1. It can be noticed from the figure that the blends B20 & B40 have less NO$_X$ emission than diesel fuel. Normally nitric oxide emissions are higher for methyl ester blends of rubber seed oil than diesel fuel, due to the oxygen concentration in the biodiesel and the presence of nitrogen present in the atmospheric air.

Fig.5.33 Variation of Oxides of nitrogen with brake power

![CR=20](image-url)
It has been reported that the biodiesel with a higher cetane number had comparable NO\textsubscript{X} emissions with diesel fuel [32]. The nitric oxide emissions for Diesel, B20, B60, and B100 are 600, 470, 550, 670 & 740ppm. From the graph it can be noticed that for blend B20 produces less emission than the diesel fuel due to its complete combustion characteristics.

5.5 COMBUSTION AND EMISSION CHARACTERISTICS OF BLENDS OF BIODIESEL AT CR= 22

5.5.1 Brake Thermal Efficiency

The variation of brake thermal efficiency with respect to brake power for different fuels for a compression ratio of 22 is considered for the present analysis is presented in Fig.5.34.
At higher compression ratios it has been noticed that the methyl ester blend B40 has the capability to attain higher efficiency when comparing with the diesel. The brake thermal efficiencies for Diesel, B20, B40, B60 & B100 are 30.23, 33.43, 36.54, 28.47 & 27.35% respectively. By analyzing the graph when the biodiesel blend gets increases, the thermal efficiency starts decreasing due to reduction in heating value [26]. This is mainly due to longer ignition delay result in late burning which leads to a reduction in thermal efficiency. Higher thermal efficiency is achieved for the blend B40 than the diesel fuel at higher compression ratios may be due to its complete combustion takes place inside the engine cylinder.

5.5.2 Specific fuel Consumption

The specific fuel consumption with respect to brake power when the engine is running at a compression ratio of 22:1 is shown in Fig.5.35. Normally specific fuel consumption decreases with increase in load.

![Fig.5.35 Variation of Specific fuel consumption with brake power](image-url)
It can be noticed from the graph that for the blends of B60 and B100 the values are recorded as 0.32 and 0.35 kg/kWh at full load conditions. Increase in composition of methyl ester reduces its heating value which leads to higher specific fuel consumption.

5.5.3 Peak Cylinder Pressure

The variation of peak cylinder pressure with brake power for different blends of biodiesel is compared with diesel for compression ratio 22 is indicated in Fig.5.36. The peak value of pressure depends on the fuel properties, combustion process and the engine load. As shown in figure the peak pressure for all the tested fuels increases with load, this may be due to more amount of fuel get burned and the consequent release of heat at higher loads. The peak pressure varies from 41 bar to 67 bar, while that of diesel it varies from 41 bar to 61 bar, higher peak pressure is seen for B100.

![Fig.5.36 Variation of Cylinder pressure with brake power](image-url)
The combustion can be noticed earlier for biodiesel and its blends at all engine loads, than diesel fuel due to the decrease in ignition delay period at higher engine loads which minimizes the delay period.

### 5.5.4 Combustion Duration

The variation of combustion duration with brake power for different blends of biodiesel is compared with diesel for compression ratio of 22 is indicated in Fig.5.37. The peak value of combustion duration depends on the fuel properties, combustion process and the engine load. The combustion duration for B60 & B100 is almost same and the highest value is noted as $132^\circ$ CA and the lowest value for diesel is about $124^\circ$ CA when the engine is running at full load conditions.

![Variation of Combustion duration with brake power](image)

**Fig.5.37 Variation of Combustion duration with brake power**
5.5.5 Exhaust Gas Temperature

The variation of exhaust gas temperature with respect to load for different fuels tested when running at a compression ratio of 22:1 is plotted in Fig.5.38. When the engine is running at higher compression ratios the exhaust gas temperature of various blends is higher than diesel. The maximum exhaust gas temperature has been recorded as 350°C for rubber seed oil methyl ester where as for diesel it is found as 280°C for diesel. The mean exhaust gas temperature for B20, B40, B60 & B100 were 295, 317, 330 & 350°C. When the combustion takes place inside the engine cylinder, incomplete combustion takes place for rubber seed oil methyl ester blends.

![Exhaust Gas Temperature Graph](image)

*Fig.5.38 Variation of Exhaust gas temperature with brake power*

5.5.6 Pressure - Crank angle Diagram

The cylinder pressure crank angle of diesel and blends of biodiesel for a compression ratio of 22:1 is shown in Fig.5.39. It is observed that cylinder pressure of
diesel is higher than that of Rubber seed oil methyl ester for any operating load conditions.

The rubber seed based biodiesel has greater diesel index value than the diesel and hence reduced ignition delay. This leads to cylinder pressure rise, controlled by the rate of injection and mixing. Also it is observed that as the speed increases, the peak value of cylinder pressure is reduced for both diesel and blends of biodiesel. This is because, the ignition delay increases as the speed increases. This longer delay leads to sufficiently late ignition occurring in the expansion process, resulting in quenching of burning process. This consequently leads to incomplete combustion and lower fuel conversion efficiency and power output.

![P-Theta Diagram](https://via.placeholder.com/150)

Fig.5.39 Variation of Cylinder pressure with Crank angle
5.5.7 Heat Release Rate

Increase in viscosity of the blend increases the heat release rate. When the engine is fuelled with diesel the heat release rate is reduced due to low viscosity of fuel. The heat release rate of standard diesel is higher than oil blend due to its reduced viscous nature and better spray formation with high compression ratio in the engine cylinder. The profiles produces different ignition delays, longer delays allow more fuel to mix with in the combustible limits during the delay. It can be observed from Fig.5.40 that in the case of diesel for a compression ratio of 22:1 the heat release rate increases than the biodiesel, the reason behind this is due to good atomization and evaporation of diesel with the mixing of air in the combustion chamber during the combustion period.

Fig.5.40 Variation of Heat Release with Crank angle
The heat release rates throughout the combustion process are increased by increasing the fuel injection rate; these changes increase the fuel air mixing rates within the fuel spray and therefore increase the heat release rate during the mixing phase of controlled combustion.

5.5.8 Smoke

The smoke from the Diesel engine using methyl esters of rubber seed oil and its blends with Diesel for a compression ratio of 22:1 is shown in Fig.5.41. It may be observed that smoke decreases with decrease in biodiesel blends. This is due to uniform mixture present inside the cylinder which leads to complete combustion and higher heat release rate in the premixed combustion phase.

![Fig.5.41 Variation of Smoke with brake power](image_url)
The lowest smoke is seen for B20, because of complete combustion takes place inside the engine which increases the performance of the engine. It may be due to the chemical reaction takes place in the fuel during combustion in the presence of oxygen.

**5.5.9 Carbon monoxide (CO)**

The variation of carbon monoxide emission for the blends of methyl esters of rubber seed oil and diesel for compression ratio 22:1 is shown in Fig.5.42. The carbon monoxide emission of the blend B20 is close to that of standard diesel. The other blends B60 and B100 have slightly higher carbon monoxide emissions.

![Fig.5.42 Variation of Carbon monoxide with brake power](image-url)

It is found that for B20 & B40 the CO emission reduces than pure biodiesel, this is due to the fact that oxygen present in the blends may lead to complete combustion there by lowering CO emissions.
5.5.10 Unburned Hydrocarbons (HC)

The variation of hydrocarbon with respect to brake power for blends of methyl esters of rubber seed oil is compared with diesel when the engine is running at a compression ratio of 22:1.

It has been observed from the Fig.5.43 that the variation of hydrocarbon emission increases with increase in load, and a huge difference of variation can be noticed in their emission values. It shows that the hydrocarbon emission for blend B20 is higher. It varies from 38ppm to 73ppm from no load to full load. The other blends B40, B60, B100 and Diesel fuel produces lesser hydrocarbon emissions.

![Fig.5.43 Variation of Hydrocarbon with brake power](image)

5.5.11 Oxides of Nitrogen (NO$_X$)

The variations on the NO$_X$ emissions at different engine loads are compared between diesel and Rubber seed oil biodiesel for a compression ratio of 22:1 is shown in Fig.5.44. It can be seen from the figure that the blend B20 is having less NO$_X$ emission than Diesel.
The increase of exhausted NO\textsubscript{X} concentration at early injection timing is thought to be caused by not only by the reduction in equivalence ratio but also the increase in flame temperatures caused by more fuel-air mixture burning in premixed combustion phase due to longer delay [32, 33]

5.6 SUMMARY

The brake thermal efficiency for bio-diesel is slightly better than that of diesel at all compression ratios. Moreover, the optimum CR ratio for bio-diesel is found to be 20 and that for standard diesel is 18, and uneven combustion and vibrations are observed at higher CR’s. Since it is a test rig which can withstand up to CR 22, however in actual biodiesel engine it has to be designed for CR20 for biodiesel. The SFC for bio-diesel is somewhat higher than diesel due to higher specific gravity of bio-diesel. The shortcoming of viscous nature of the fuel is compensated by the presence of oxygen in the fuel yielding better combustion properties and lower emissions. The lower EGT for bio-diesel reduces the NOx emission and the CO emission decreases with increase in CR due to improved atomization of the fuel.