CHAPTER V

RESULTS AND DISCUSSION
CHAPTER-V
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Coconut oil methyl ester (COME) is blended with triacetin to improve viscosity properties of biodiesel. Various blends of the above with different triacetin quantities are tested to explore the benefits in total replacement of diesel in this experimentation. Normally, diesel fuel or biodiesel detonates to certain extent due to combustion heterogeneity. This detonation trend can be contained to some extent by certain triacetin percentage mixed as an additive to COME biodiesel. Triacetin is known for its anti-knocking property with gasoline. Proportions with percentages ranging from 5%, 10%, 15%, 20% and 25% by volume have been tried with biodiesel as main fuel and the engine performance has been evaluated. Improvement in most aspects can be observed with certain amount of blend percentage. The knocking frequency has been calculated based on sonic frequency in the engine diametric direction and the percentage of triacetin was arrived at, with the reduction in knocking amplitude at the calculated frequency of knocking. The engine tested was the laboratory based, four stroke, vertical single cylinder, direct injection diesel engine, which generates 5 hp at a rated rpm of 1500. The auto ignition temperature of triacetin is 458°C, which is higher than that of diesel and biodiesel. The calorific value of triacetin is in the range of 20,000 kJ/kg which is lower than that of COME biodiesel fuel value 36,000 kJ/kg. Triacetin contains 44% of molecular oxygen which doesn’t allow the main fuel to starve out of Oxygen under engine loading conditions. Triacetin improves the shelf life of biodiesel as can take in to the extent of 7% of water. Coconut oil methyl ester itself has an advantage of lower iodine value of seven (which is an indication of degree of unsaturated condition) for more shelf life.

5.1 Study of cylinder pressures during combustion

Combustion pressures in the combustion chamber have been recorded with respect to the TDC position. For specific study of the start of combustion and the specific heat of fuel mixture employed, small combustion duration from 350° to 400° which encompasses the TDC position in between at 360° has been chosen. There is relative pressure rise at the start of combustion due to temperature rise because of lower specific
heat of mixture and higher convective heat transfer coefficient for various mixtures. Thermal properties of the bio-fuel change with the blending of soluble triacetin. The blend with 10% Triacetin, as can be seen from the figures 5.1 to 5.4 has shown improvement in the combustion pressure generation starting from the start of combustion at full load and three fourth’s full load. This particular blend has proved its consistent performance in the tail pipe emissions and engine cylinder vibrations. The pressure variations at two important loads, which normally every diesel engine is advised to run have been shown in the above said figures. The modus operandi of pressure variation is same for the two loads taken into consideration.

![Fig.5.1 Input pressure data signatures drawn for limited range of 340° to 400° crank angle for diesel, biodiesel and for all biodiesel-additive blends at full load](image-url)
Fig. 5.2  Delay period plot for diesel, biodiesel and biodiesel-additive blends at full load

Fig. 5.3  Input pressure data signatures drawn for limited range of 340° to 400° crank angle for diesel, biodiesel and for biodiesel-additive blends at 75% full load
5.2 Net and cumulative heat release rate comparison

The net and cumulative heat release rate graphs at full load and 75% full load are shown from 5.5 to 5.8. It can be observed that the net heat release rate peak is increasing with the increase of triacetin in the blend. The 10% Triacetin blend falls in between the diesel and biodiesel in the net and cumulative heat release aspects and emerges as the best alternative to the conventional diesel. The cumulative heat graphs decipher consistent performance both in the premixed and diffused combustion zones for 10% triacetin blend with biodiesel. The 5% triacetin joins the band wagon of 20% and 25% triacetin blends with respect to the low profile diffused combustion as shown in the figures 5.5 to 5.8.

Ignition delay decreased in the case of 10% Triacetin blend as this blend is optimal in reducing vibration and to improve combustion quality. Heat release rate curves (5.5 to 5.8) computed indicate better performance in case of 10% triacetin blend in the premixed as well as in diffused zone. With the increase of triacetin quantity in the blend, the diffused combustion deterioration has taken place as seen in the figures. The 5% triacetin blend could not gain sensible heat from the air fuel mixture and converse is
true for the 10% blend. This trend can be observed from the pressure crank angle diagrams as shown in figures 5.1 to 5.4. There is dramatic change in the process coefficient with the percentage of triacetin mix especially at 5% and 10% which affects \( C_p \) and \( C_v \) values. The cumulative heat release rate curves also exhibit the same thing in the case of 5% and 10% triacetin mixes with an advantage to 10% triacetin blend in the diffused combustion zone. There is a rapid fall of heat release in case of 5% triacetin.

![Fig.5.5 Net heat release rates for diesel, BD and BD-T additive blends at full load](image1)

![Fig.5.6 Net heat release rates for diesel, BD and BD-T additive blend at 75% full load](image2)
**Fig. 5.7** Cumulative heat release rates for diesel, BD and BD-T additive blend at **full load**

**Fig. 5.8** Cumulative heat release rates for diesel, BD and BD-T additive blend at **75% full load**
5.3 Performance Analysis:

Figures 5.9 and 5.10 indicate thermal efficiency and brake specific fuel consumption of the fuel alternates shown in the right hand side index box. Biodiesel and diesel exhibited best performance at lower equivalence ratios. Biodiesel, as it is known, generated better thermal efficiency at all loads. Referring to the equivalence ratio for the fuels tested, it has increased with the increase of triacetin in the blend but the extent of increase is comparatively lower than that when compared to neat diesel and biodiesel. This may be because of lower calorific value and higher boiling point of triacetin. Figures from 5.11 to 5.18 depict different engine parameters with respect to equivalence ratio and engine load in KW. All parameters exhibited uniformity, except the differential pressure of combustion for 25% triacetin blend which has increased abruptly with the load on the engine as shown in figure 5.17 indicating the maximum blend percentage one can try up to. For 10% triacetin blend fuel table 5.1 depicts the better performance in the generation of combustion pressure and its parameters.

<table>
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<tr>
<th>S.No</th>
<th>Fuel</th>
<th>Indicated Power (hp)</th>
<th>IMEP (bar)</th>
<th>Peak pressure (PP)</th>
<th>Peak pressure Position w.r.t to TDP</th>
<th>Max.Differential pressure (bar)</th>
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<tr>
<td>1</td>
<td>Diesel</td>
<td>5.17</td>
<td>7.5</td>
<td>60.5</td>
<td>+10</td>
<td>7.4</td>
</tr>
<tr>
<td>2</td>
<td>Biodiesel</td>
<td>4.97</td>
<td>7.2</td>
<td>61.9</td>
<td>+10</td>
<td>6.3</td>
</tr>
<tr>
<td>3</td>
<td>5%Triacetin+95%COME</td>
<td>4.37</td>
<td>6.3</td>
<td>60.9</td>
<td>+10</td>
<td>6.2</td>
</tr>
<tr>
<td>4</td>
<td>10%Triacetin+90%COME</td>
<td><strong>4.95</strong></td>
<td><strong>7.2</strong></td>
<td><strong>62.1</strong></td>
<td><strong>+9</strong></td>
<td><strong>7.1</strong></td>
</tr>
<tr>
<td>5</td>
<td>15%Triacetin+85%COME</td>
<td>4.78</td>
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<td>61.9</td>
<td>+10</td>
<td>6.3</td>
</tr>
<tr>
<td>6</td>
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<td>4.3</td>
<td>6.2</td>
<td>60.9</td>
<td>+7</td>
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</tr>
<tr>
<td>7</td>
<td>25%Triacetin+75%COME</td>
<td>4.56</td>
<td>6.6</td>
<td>63.6</td>
<td>+12</td>
<td>7.4</td>
</tr>
</tbody>
</table>
Fig. 5.9 Variation of brake thermal efficiency versus equivalence ratio of the engine

Fig. 5.10 Variation of brake specific fuel consumption versus equivalence ratio of the engine
Fig. 5.11 Variation of fuel consumption with brake power of the engine

Fig. 5.12 Variation of equivalence ratio with load on the engine

Fig. 5.13 Variation of peak pressure verses load on the engine

Fig. 5.14 Variation of IMEP verses load on the engine

Fig. 5.15 Variation of brake thermal efficiency verses load on the engine

Fig. 5.16 Variation of exhaust temperature verses equivalence ratio of the engine
5.4 Discussion on Engine Emissions

Black color bars indicate the absolute values of the diesel fuel emissions and other negative side colored stalks indicates decrease from the absolute value of diesel. For example, in the figure 5.19, yellow stalk indicate HC emission of biodiesel and at full load the absolute value of HC emission for the biodiesel is $132-72= 60$ ppm. The extent of decrease in that particular emission value can be easily observed in the graph.

Hydrocarbon emissions decrease with the loading of the engine and 10% triacetin blend produced remarkable value of decrease (99 ppm). Biodiesel is known for its efficiency to reduce emissions except NOx. Triacetin blend with biodiesel further helped in the reduction of HC by 27ppm.

Carbon monoxide emissions (figure 5.20) are reduced better at lower loads and CO2 emissions reduction (figure 5.21) is nominal at all loads of the engine.

NO emission trade off is not observed with HC emission because the figure 5.22 envisage decrease of NO emission with the load and with the increase of triacetin percentage. For 10% triacetin the decrement is 300 ppm at full load operation of the engine.

Smoke levels in HSU for neat biodiesel at the loads tested are the best, when compared to the other fuel blends tested as shown in figure 5.23. The most competitive
blend emerged is 20% triacetin in the context of smoke emission with respect to biodiesel.

Fig. 5.19 Variation of hydrocarbon emission verses load on the engine

Fig. 5.20 Variation of carbon monoxide emission verses load on the engine
Fig. 5.21 Variation of carbon dioxide emission verses load on the engine

Fig. 5.22 Variation of NO emission verses load on the engine
5.5 Summery of Results on engine performance

The performance and emission parameters were measured for diesel, COME and COME with Triacetin additive blends without modifications in the engine operating parameters, and the results are summarized as follows:

- **Brake Thermal Efficiency**: Figure 5.9 gives the details of brake thermal efficiency versus equivalence ratio of neat fuel and the blends. It can be ascertained from the figure that the equivalence ratio is increasing with the triacetin additive percentage. The equivalence ratio and Thermal efficiency, both will increase, but are governed by different equations entailing non-synchronous increase. The implicit parameter in Thermal Efficiency is Calorific Value, which decreases with the increase in fuel consumption, as the Calorific Value of Triacetin is comparatively lesser. The 10% triacetin blend yielded better thermal efficiency curve at higher loads as can be observed.

- **Brake Specific Fuel Consumption**: Figure 5.10 envisages the BSFC performance of the engine with different blend fuel samples. For 10% triacetin blend, the part load performance is observed better corroborating with the brake thermal efficiency results as described above.
• Exhaust Gas Temperature: From figure 5.16, there is marginal fall in the exhaust gas temperatures with respect to increase in the load on engine by using higher percentages of triacetin and this may be because of lower heat release rate in the diffused combustion at lower calorific value of the blended fuel.

• Hydrocarbon (HC) Emission: There is 75% maximum reduction in HC emission with the triacetin blending which can be observed from the figure 5.19. As the load on the engine increases, the HC emission decreases at all percentages of blend fuels tested.

• Carbon monoxide (CO) Emission: CO emission also reduced by 50% [maximum] from figure 5.20 and trade off with other emissions has not been observed.

• Carbon Dioxide (CO2) Emission: From figure 5.21, there is a reduction of nearly maximum 10% of CO$_2$ emission with the blends and at higher loads.

• Nitrogen Oxide (NO) Emission: NO emission decreased with the load on the engine and especially more decrease can be observed at three fourth of full load. Nearly 28 to 29% maximum decrease in this emission can be observed with the triacetin blend from figure 5.22.

• Engine smoke levels have decreased substantially with the triacetin additive application as shown in figure 5.23.

5.6 Engine vibration study

Figures 5.24 to 5.28 indicate the average spectrum values of the engine cylinder run at different loads and different combinations of blend fuels which also include neat diesel and biodiesel. The engine run with 10% triacetin blend at full load generated lowest vibration levels at the points defined.

The time waves were recorded on the cylinder head and the wave form in the explosion stroke is isolated and represented against pressure signature to study the inner details of combustion (figures 5.29 to 5.35). This plotting is based on nullifying the delay period between the peak pressures generated in the combustion chamber to the maximum vibration peak in the time wave form picked up from the explosion stroke.
Fig. 5.24 Variation of average spectrum values of the engine at no load

Fig. 5.25 Variation of average spectrum values of the engine at 25% full load

Fig. 5.26 Variation of average spectrum values of the engine at 50% full load

Fig. 5.27 Variation of average spectrum values of the engine at 75% full load

Fig. 5.28 Variation of average spectrum values of the engine at full load
This gives a better picture of understanding of the ignition propensity with different fuel combinations.

The increase in delay period can be ascertained from $0.20ms$ to $1.70ms$ for $5\%$ to $25\%$ triacetin blends which can be observed from the figures $5.29$ to $5.35$. There is simultaneous rise in the engine vibration after the start of ignition with respect to increase in triacetin percentage. The triacetin $25\%$ blend (figure $5.33$) reflected knocking condition of the engine with the vibration acceleration, and amplitude rise to about $40g$ which is coinciding with the differential pressure rise explained earlier (figure $5.17$), whereas $10\%$ triacetin blend (figure $5.30$) exhibited smoother combustion with pure harmonic reduction during explosion stroke, eliminating mixed frequencies. The envelope of the time wave exactly coincides with the pressure variation in synchronous exhibition of the two signatures i.e. pressure exciter and vibration generation wave.

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**Fig. 5.29** Time wave recorded vertical on the cylinder head during explosion stroke at full load operation and it’s corresponding combustion pressure trace of blend fuel with $5\%$ triacetin and $95\%$ bio-diesel.
Fig. 5.30 Time wave recorded vertical on the cylinder head during explosion stroke at full load operation and it’s corresponding combustion pressure trace of blend fuel with 10% triacetin and 90% bio-diesel.

Fig. 5.31 Time wave recorded vertical on the cylinder head during explosion stroke at full load operation and it’s corresponding combustion pressure trace of blend fuel with 15% triacetin and 85% bio-diesel.
Fig. 5.32 Time wave recorded vertical on the cylinder head during explosion stroke at full load operation and its corresponding combustion pressure trace of blend fuel with 20% triacetin and 80% bio-diesel.

Fig. 5.33 Time wave recorded vertical on the cylinder head during explosion stroke at full load operation and its corresponding combustion pressure trace of blend fuel with 25% triacetin and 75% bio-diesel.
**Fig. 5.34** Time wave recorded vertical on the cylinder head during explosion stroke at Full load operation and it’s corresponding combustion pressure trace with *neat bio-diesel operation*.

**Fig. 5.35** Time wave recorded vertical on the cylinder head during explosion stroke at full load operation and it’s corresponding combustion pressure trace with *neat diesel operation*.
5.6.1 Engine Knock estimation

The phenomenon of knock has been a major limitation for CI and SI engines since the beginning of their evolution. Engine knock has its name from the audible noise that results from auto ignitions in the unburned part of the gas in the cylinder. The most probable locations for harmful self-ignitions lie in the proximity of hot surfaces, i.e., piston, cylinder walls and in the largest possible distance from the injector & spark plug. This can be explained by the concept of pre-reaction level. In this notion, the auto ignition is a result of the chemical state of the unburned gas exceeding a critical level in which enough of highly reactive radicals are formed, leading to a spontaneous ignition. This pre-reaction level, being proportional to the concentration of radicals, increases over a period of time, primarily under the influence of high temperatures and secondarily, high pressures. The pressure in the cylinder can be assumed to be spatially constant (it varies with time) since the speed of sound, at which the pressure is equalized. In contrast, the temperature varies significantly within the cylinder volume. In unburned gas, regions of the highest temperature levels are located at the boundary layers close to hot surfaces. In those regions the flow of gas is slow and therefore heat from the walls is transferred to a small volume during a long period of time.

If the mass fraction of unburned gas at the time of auto ignition is large and its pre-reaction level is high (i.e., close to critical), several adjacent hot spots are ignited and merge to a fast expanding “reaction region” such that all of the highly reactive unburned gas burns almost at once. Under these conditions the chemical reactions spread faster than the speed of sound, resulting in insufficient pressure equalization. This in turn leads to shock waves and consequently to harmful pressure peaks in the cylinder.

The pressure waves resulting from knocking combustion have a characteristic frequency that depends mostly on the characteristic length of the oscillation and the speed of sound in the combustion chamber. Assuming that the cylinder is filled with air (modeled as an ideal gas) at a temperature of 2000K, the speed of sound $v_{cyl}$ is

$$C_{cyl} = \sqrt{k.R.\gamma_{cyl}} = \sqrt{1.4 \times 287 \frac{J}{kg.K} \times 2000K} \approx 896 \frac{m}{s}.$$
Where $B$ is the cylinder bore and $\alpha_{m,n}$ the vibration mode factor. This parameter $\alpha_{m,n}$ can be approximated using the analytical solution of the general wave equation in a closed cylinder with flat ends. For the first circumferential mode this yields $\alpha_{1,0} = 1.841$. For an engine with a bore of $B = 80\text{mm} = 0.080\text{m}$ the frequency related to knock therefore is

$$f_{\text{knock}} = \frac{C_{\text{cyl}} \cdot \alpha_{1,0}}{\pi \cdot B} = \frac{896 \cdot \frac{m}{s} \cdot 1.841}{\pi \cdot 0.080\text{m}} = 6.564\text{kHz}$$

and severe knock only occurs if auto ignition starts before $X_B = 70\%, 75\%, \text{or} 80\%$.

Figure 5.36, envisages the mean effective pressures for bio-diesel and petro-diesel at full load engine operation falling in the knocking zone and for blends with triacetin the mean effective pressures fall below 6.5 bar and hence no severe knocking at 1500rpm. Figures 5.37 to 5.43 envisage the amplitudes of knocking frequencies with neat oils and with triacetin blends. This indicates that at 10% triacetin blend, the knocking amplitude is minimum for the reading obtained on the engine cylinder head, in radial direction and in line crank shaft. This direction is chosen with the view that there won’t be mixed effect like piston slap in other radial direction and thrust transfer to the piston in the vertical direction and thus knocking can be fully realized in the direction inline crank. The knocking frequencies are varying by little margin around 6500Hz because of the combustion temperature variation with respect to the blend combination of triacetin.

![Fig. 5.36 Full-load curve and knocking operating regions under the assumption for different burnt mass fractions ‘$X_B$’](image-url)
Fig. 5.37 FFT spectrum indicating **Knocking frequency** and acceleration amplitude for **neat diesel** application. Vibration Measurement is made in the radial direction of cylinder in line crank shaft axis.

Fig. 5.38 FFT spectrum indicating **Knocking frequency** and the acceleration amplitude for **neat Bio-diesel** application. Vibration Measurement is made in the radial direction of cylinder in line crank shaft axis.

Fig. 5.39 FFT spectrum indicating **Knocking frequency** and the acceleration amplitude for **5% Triacetin + 95% Biodiesel** blend application. Vibration Measurement is made in radial direction of the cylinder in line crank shaft axis.
Fig. 5.40 FFT spectrum indicating Knocking frequency and the acceleration amplitude for 10% Triacetin + 90% Biodiesel blend application. Vibration Measurement is made in radial direction of the cylinder in line crank shaft axis.

Fig. 5.41 FFT spectrum indicating Knocking frequency and the acceleration amplitude for 15% Triacetin + 85% Biodiesel blend application. Vibration Measurement is made in radial direction of the cylinder in line crank shaft axis.

Fig. 5.42 FFT spectrum indicating Knocking frequency and the acceleration amplitude for 20% Triacetin + 80% Biodiesel blend application. Vibration Measurement is made in radial direction of the cylinder in line crank shaft axis.
The following Chapter V deals with conclusions of the experiments done on DI diesel engine with biodiesel-triacetin additive blends at various percentages by volume.

Fig. 5.43 FFT spectrum indicating Knocking frequency and the acceleration amplitude for 25% Triacetin + 75% Biodiesel blend application. Vibration Measurement is made in radial direction of the cylinder in line crank shaft axis.