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(Full length research article)

Performance, Emission and Cylinder Vibration studies of DI-Diesel Engine with COME-Triacetin Additive Blends

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Abstract

Triacetin [$C_9H_{14}O_6$] *is the anti-knocking additive used along with the bio-diesel in DI- diesel engine. Knocking to some extent can be detected with the usage of diesel fuel and neat bio-diesel. The usage of T- additive suppressed knocking, improved the performance and reduced tail pipe emissions. Comparative study is conducted using petro-diesel, bio-diesel, and with various additive blends of bio-diesel on DI- diesel engine. Coconut oil methyl ester (COME) is used with additive triacetin (T) at various percentages by volume for all loads (No load, 25%, 50%, 75% and full load). The performance of engine is compared with neat diesel in respect of engine efficiency, exhaust emissions and combustion knock. Of the five Triacetin- biodiesel blends tried, 10% Triacetin combination with biodiesel proved encouraging in all respects of performance of the engine.*

Keywords: *Performance, Biodiesel, Exhaust emissions, Additive, Triacetin, COME*

1. Introduction

Around the world, there is a growing increase in biofuels consumption, mainly ethanol and biodiesel as well as their blends with diesel that reduce the cost impact of biofuels while retaining some advantages of the biofuels. This increase is due to several factors like decreasing the dependence on imported petroleum; providing a market for the excess production of vegetable oils and animal fats; using renewable and biodegradable fuels; reducing global warming due to its closed carbon cycle by CO_2 recycling; increasing lubricity; and reducing substantially the exhaust emissions of carbon monoxide, unburned hydrocarbons and particulate emissions from diesel engines. However, there are major drawbacks in the use of biofuels blends as NOx tends to be higher, the intervals of motor parts replacement such as fuel filters are reduced and degradation by chronic exposure of varnish deposits in fuel tanks and fuel lines, paint, concrete, and paving occurs as some materials are incompatible. Here, fuel additives become indispensable tools not only to decrease these drawbacks but also to produce specified products that meet international and regional standards like EN 14214, ASTM D 6751, and DIN EN 14214, allowing the fuels trade to take place. Additives improve ignition and combustion efficiency, stabilize fuel mixtures, protect the motor from abrasion and wax deposition and reduce pollutant emissions, among other features. Two basic trends are becoming more relevant: the progressive reduction of sulfur content and the increased use of biofuels. Several additives compositions may be used as long as they keep the basic chemical functions that are active.

Emissions from diesel engines seriously threaten the environment and are considered one of the major sources of air pollution. It was proved that these pollutants cause impacts in the ecological systems, lead to environmental problems, and carry carcinogenic components that significantly endanger the health of human beings. They can cause serious health problems, especially respiratory and cardiovascular problems. Increasing worldwide concern about combustion-related pollutants, such as particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), total hydrocarbons (THC), acid rain, photochemical smog and depletion of the ozone layer has led several countries to regulate emissions and give directives for implementation and compliance. It is commonly accepted that clean combustion of diesel engines can be fulfilled only if engine development is coupled with diesel fuel reformulation or additive introduction. [1, 2] In this way, methods to reduce PM and the present work was under taken to study the performance of D I diesel engine with coconut oil methyl ester and triacetin additive blends at different percentages.

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Normally additives are used to boost the combustion hence improves fuel economy at lower emission rates.

NOx emissions include high-pressure injection, turbo charging, and exhaust after treatments or the use of fuel additives, which is thought to be one of the most attractive solutions. [3-5] Engine exhaust contains volatile organic compounds (VOCs), which embody unburned fuel emissions and other VOCs generated as byproducts of incomplete combustion (PIC). Some VOCs described as being of health concern are acetaldehyde, acrolein, benzene, 1, 3-butadiene, formaldehyde, and naphthalene. Gasoline- and diesel-powered vehicles are the largest source of VOCs in most urban areas [5].

Diesel oil is a fuel derived from petroleum and consists mainly of aliphatic hydrocarbons containing 8-28 carbon atoms with boiling points in the range of 130-370 °C. It is a blend of fractions of hydrocarbons heavier than those of the hydrocarbons in gasoline and with a lower H/C mass ratio, which determines the high emission of carbon compounds per unit of energy delivered to the engine. A reduction in consumption and improvements in the quality of diesel oil have been the object of study by various specialists, motivated by growing demands in the transport and electric sectors.

Commercially available diesel oil is a combination of fossil diesel and several additives, which are added in several amounts to perform specific functions. Among others, there are additives to (1) reduce pernicious emissions; (2) improve fluid stability over a wider range of conditions; (3) improve the viscosity index, reducing the rate of viscosity change with temperature; (4) improve ignition by reducing its delay time, flash point, and so forth; and (5) reduce wear with agents that adsorb onto metal surfaces and sacrificially provide chemical-to-chemical contact rather than metal-to-metal contact under high-load conditions. There is also an increasing trend to use blends with biomass products such as vegetable oil, ethanol, and biodiesel by increasing the use of alternative fuels. Blends of diesel and biodiesel usually require additives to improve the lubricity, stability, and combustion efficiency by increasing the Cetane number. Blends of diesel and ethanol (E-diesel) usually require additives to improve miscibility and reduce knock. Diesel additives can also be classified according to the purpose for which they are designed. Preflame additives are designed to rectify problems that occur prior to burning and include dispersants, pour point depressants, and emulsifiers, which act as cleaning agents. Flame additives are used to improve combustion efficiency in the combustion chamber, to increase cetane number, to reduce the formation of carbon deposits, to avoid oxidation reactions and contamination of fuel and filters clogging by rust, and to inhibit potential explosions caused by changes in static electricity [6]. Postflame additives are designed to reduce carbon deposits in the engine, smoke, and emissions [7].

Due to the worldwide effort to make renewable energy economically viable as well as to use cleaner fuels, additives will become an indispensable tool in global trade. Their technical specifications not only cover a wide range of subjects but also most subjects are interdependent. This makes the expertise of additives technology indispensable in the global trade of fuels. It is likely that, as energy sources become cleaner and renewable, we might find ourselves facing issues that are quite hard to overcome, and diesel additives may become a worldwide indispensable tool. The additives share in the world market should increase in the next few years as long as energy sources become cleaner and renewable.

The phenomenon of engine knock has been a major limitation for diesel 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 or initially accumulated fuel during first phase of injection. The most probable locations for harmful self-ignitions lie in proximity of hot surfaces, i.e., piston and cylinder walls, and in the largest possible distance from the spark plug or injector. This can be explained by the concept of the pre-reaction level. In this notion, the auto ignition is a result of the chemical state of 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 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, is several orders of magnitude larger than the speed of the flame propagation. In contrast, the temperature varies significantly within the cylinder volume. In the unburned gas, regions of the highest temperature levels are located in the boundary layers close to hot surfaces. In those regions the gas flow is slow and therefore the 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 **[9]** 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.

2. Experimentation

Four stroke single cylinder DI diesel engine details as shown in below and fig.1 is the schematic diagram showing various equipment modules. Experiments were conducted with neat diesel, pure COME and COME with

Triacetin [$C_9H_{14}O_6$] additive at different percentages for full load range of engine. During the test performance, exhaust emissions and smoke density parameters and cylinder vibration were measured by using indicated instruments.

Cylinder combustion pressures for each degree of crank angle were measured by engine data logger designed by Apex innovations, Pune, India. The software employed is C7112, which captures the combustion pressure data and converts it into the graphic form collecting crank angle history from the encoder and synthesizes with the real time pressure data.

Fuel consumption is measured to calculate BSFC, fuel air ratio and thermal efficiency. Exhaust gas temperatures were also recorded for all loads. Delta 1600-L exhaust gas analyzer(German Make) is used to measure CO_2, CO, HC, NO in exhaust gases at all loads and graph is drawn to compare. DC-11(E-Predict, Canada) Vibration analyzer is employed to measure the engine cylinder vibrations in all three directions. The FFT curves generated have been used to evaluate the combustion propensity at different loads and with the alternative fuel. This measurement is better way to access the knocking of the engine.

3. Engine Test Rig Details

Engine:	Vertical, 4stroke, Single cylinder, Water cooled Eddy current dynamometer
Rated power:	3.7 kW @ 1500rpm
Cylinder diameter:	80mm
Stroke length:	110mm
Compression Ratio:	16.5:1
Injection pressure:	200kg/cm^2
Injection timing:	23^0 BTDC

4. Results and discussions

The performance and emission parameters were measured for diesel COME and COME with Triacetin additive blends without modifications in the engine operating parameters.

Brake Thermal Efficiency: Figure (2) 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. This is because of lower calorific value of the additive compared to the main biodiesel. The maximum equivalence ratio difference observed is nearly 0.15 when Triacetin is being added. 10% Triacetin blend yielded better thermal efficiency curve at higher loads as can be observed.

Brake Specific Fuel Consumption: Figure (3) envisages the BSFC performance of the engine with different fuel versions and for 10% Triacetin blend the part load performance is observed better corroborating with the brake thermal efficiency described above.

Exhaust Gas Temperature**:** From figure (4) 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 of 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). As the equivalent ratio increases, the HC emission decreases at all percentages of blends tested.

Nitrogen Oxide (NO) Emission: NO emission decreases with the equivalent ratio 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 (6).

Carbon monoxide (CO) Emission: CO emission also reduced by 50% [maximum] from figure 7 and trade off with other emissions has not been observed.

Carbon Dioxide (CO2) Emission: From figure (8), there is a reduction of nearly maximum 10% of CO_2 emission with the blends and at higher loads. Engine smoke levels have decreased substantially with the additive application as shown in figure 9.

10% Triacetin [$C_9H_{14}O_6$] **blend** with bio-diesel is the most economical one in reducing emissions as can be observed from the figures from 5 to 9 in which absolute values of diesel against the reduction/ increase by percent for blends have been shown. Triacetin blend with the bio-diesel has decreased both the HC and NO emissions. NO emission decrease is most important with the additive mixing and it may be because of lesser hydrocarbon availability with the dilution of Triacetin and the comparative rarity of fuel elements reduces the combustion temperatures.

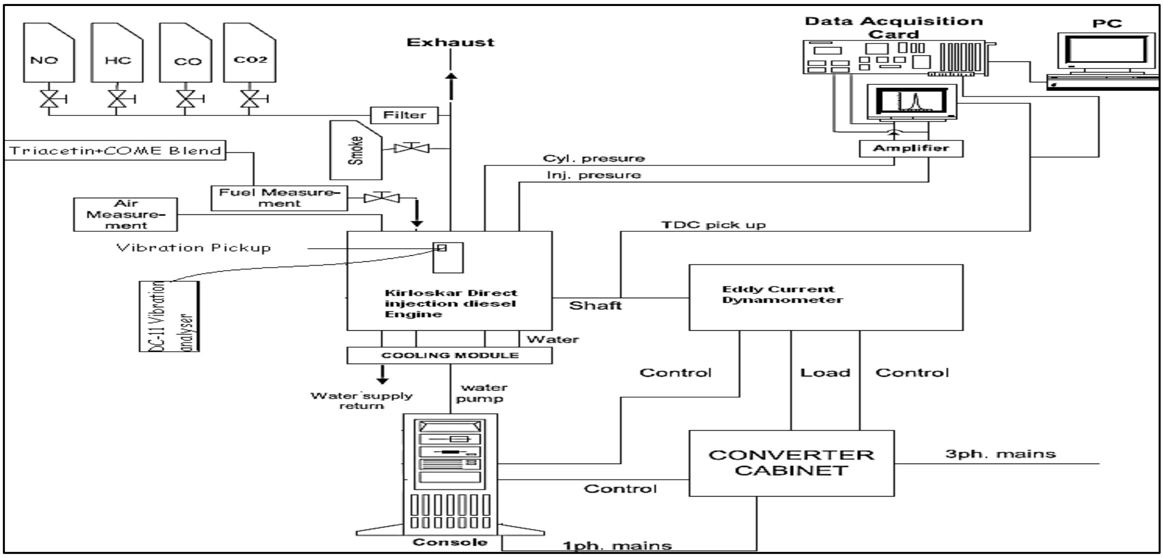


Fig.1 Schematic Diagram representing of the engine and instrumentation

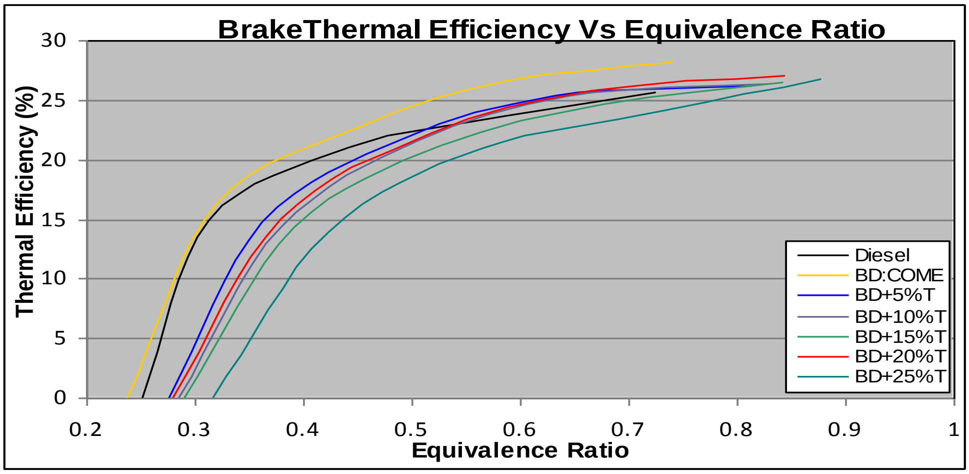


Fig.2 Variation of brake thermal efficiency V/s equivalent ratio

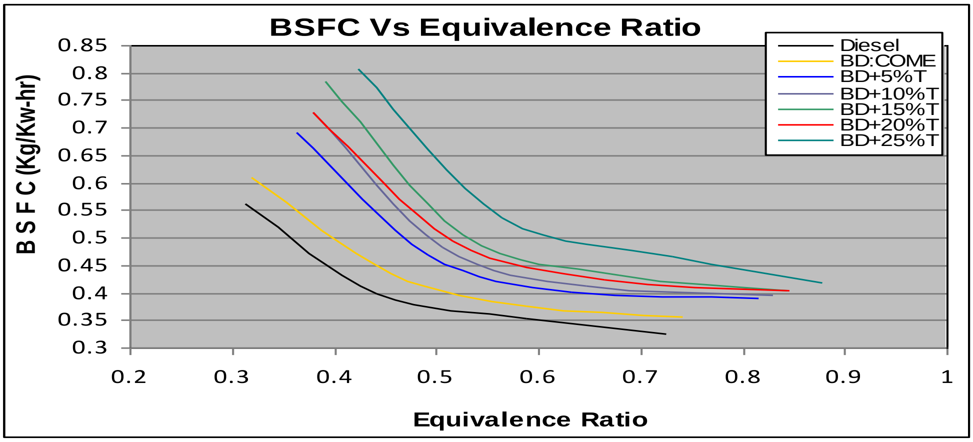


Fig.3 Variation of bsfc V/s equivalence ratio of engine

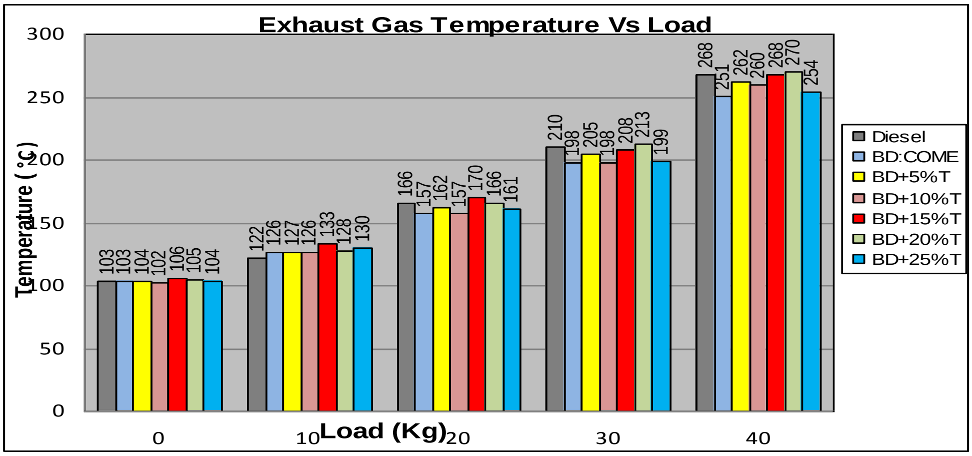


Fig.4 Variation of exhaust gas temperature V/s load on engine

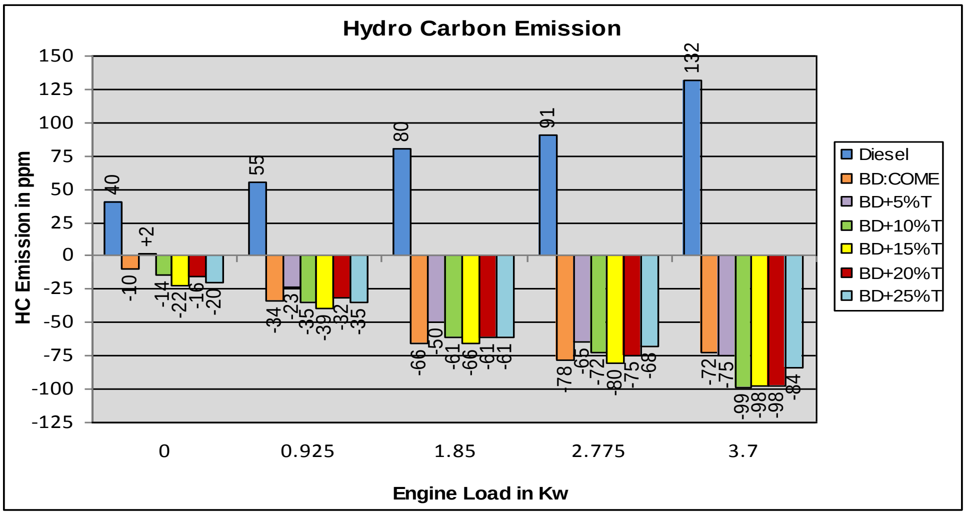


Fig.5 Variation of hydrocarbon emission V/s load on engine

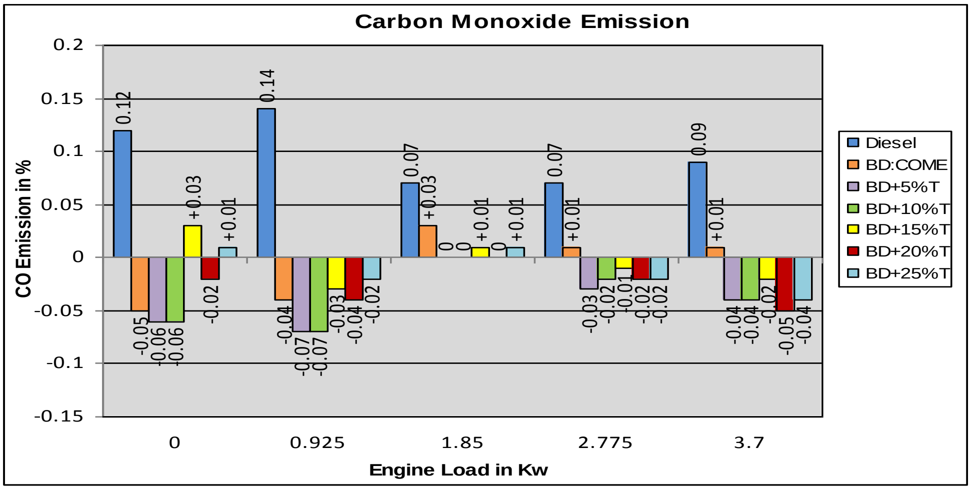


Fig.6 Variation of carbon monoxide emission V/s load on engine

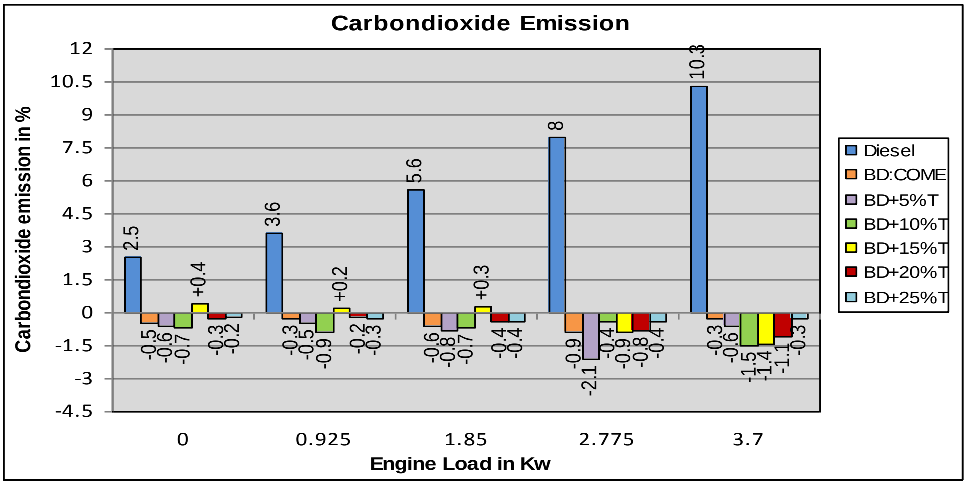


Fig.7 Variation of carbon dioxide emission V/s load on engine

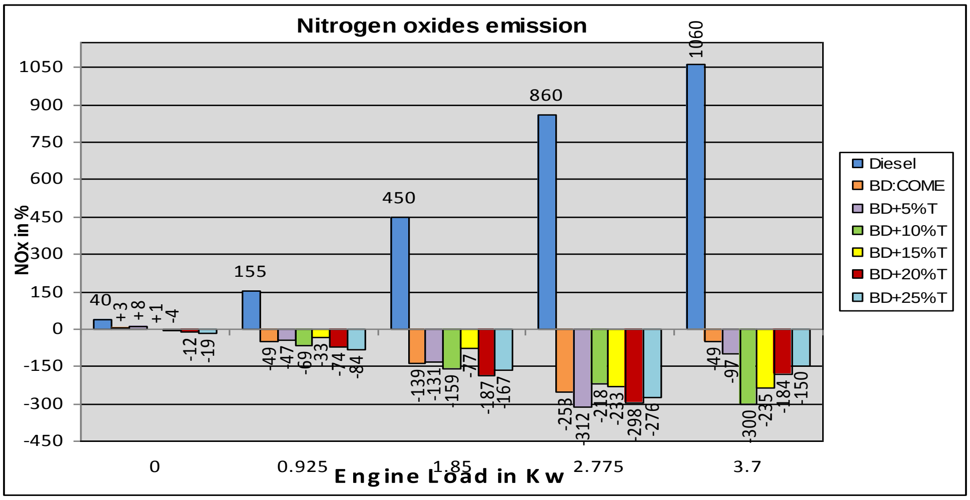


Fig.8 Variation of NO emission V/s load on engine

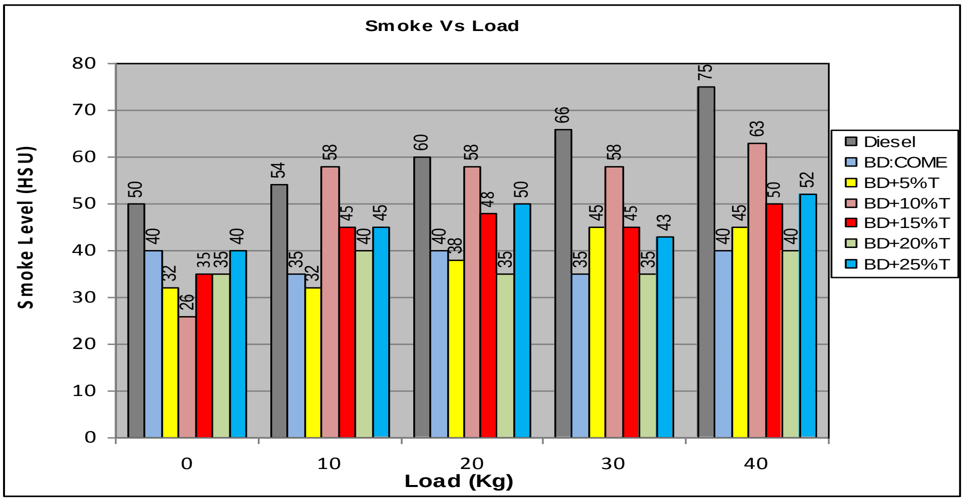


Fig.9 Variation of smoke level V/s load on engine

4.1 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 proximity of hot surfaces, i.e., piston and cylinder walls, and in the largest possible distance from the Injector & spark plug. This can be explained by the concept of the 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 highly reactive radicals are formed, leading to a spontaneous ignition. This pre-reaction level, being proportional to the concentration of radicals, increases over time, primarily under the influence of high temperatures and, secondarily, high pressures. to a small volume during a long period of time 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 the unburned gas, regions of the highest temperature levels are located in the boundary layers close to hot surfaces. In those regions the gas flow is slow and therefore the heat from the walls is transferred.

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 [8] 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 [10]. Assuming that the cylinder is filled with air (modeled as an ideal gas) at a temperature of 2000K [ϑ_{cyt}], the speed of sound is

$$C_{cyt} = \sqrt{k.R.\vartheta_{cyt}} = \sqrt{1.4.287\frac{J}{kg.K}.2000K} \approx 896\frac{m}{s}$$

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 = 80mm = 0.080m the frequency related to knock therefore is

$$f_{knock} = \frac{C_{cyl}}{\pi.B}.\alpha_{1,0} = \frac{896\frac{m}{s}.1.841}{\pi.0.08m} = 6.566kHz$$

and severe knock only occurs if auto ignition starts before X_B = 70%, 75%, or 80%. [9].

Figure (9) envisages the mean effective pressures for bio-diesel and petro-diesel at full load engine operation falling in the knocking zone and for the blends with Triacetin the mean effective pressures fall below 6.5 bar and hence no severe knocking at 1500rpm. Figures 11 to 17 envisage the amplitudes of knocking frequencies with neat oils and with Triacetin blends. This indicate that at 10% Triacetin blend, the knocking amplitude is minimum for the reading taken on the cylinder head of the engine in the radial direction 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.

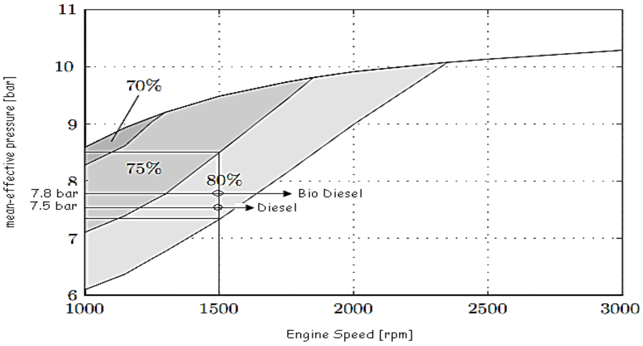
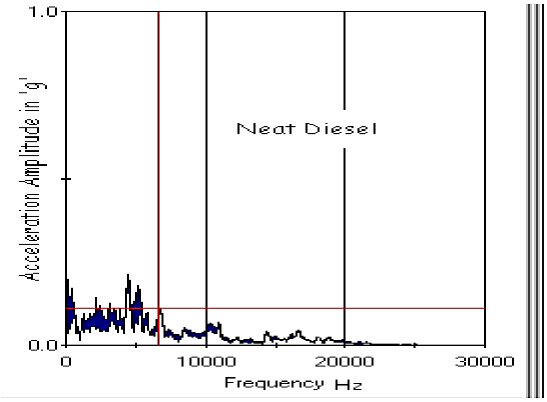


Fig. 10 Full-load curve and knocking operating regions under the assumption for different burnt mass fractions 'X_B' [9]

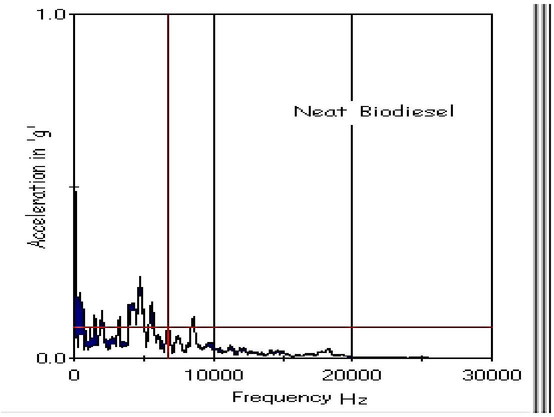


Spectral Setup

Magnitude:	Acceleration
Point:	"18- radial on the CY
Machine:	DE Vibration at full l
Train:	FUELS
Plant	DI Diesel engine wit
Date:	17/06/2011 10:11
Value:	**0.110706 g**
Frequency	**6640 Hz (416)**
No. of Lines:	1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S] Show SBA

Fig. 11 FFT spectrum indicating *Knocking frequency* and the acceleration amplitude for neat diesel application. Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.

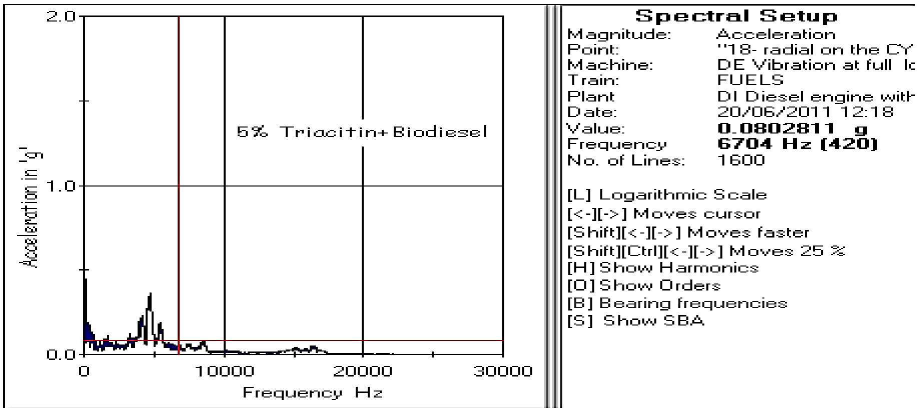


Spectral Setup

Magnitude:	Acceleration
Point:	"18- radial on the CY
Machine:	DE Vibration at full l
Train:	FUELS
Plant	DI Diesel engine wit
Date:	17/06/2011 11:48
Value:	**0.0902055 g**
Frequency	**6736 Hz (422)**
No. of Lines:	1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S] Show SBA

Fig.12 FFT spectrum indicating *Knocking frequency* and the acceleration amplitude for neat Bio-diesel application. Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.

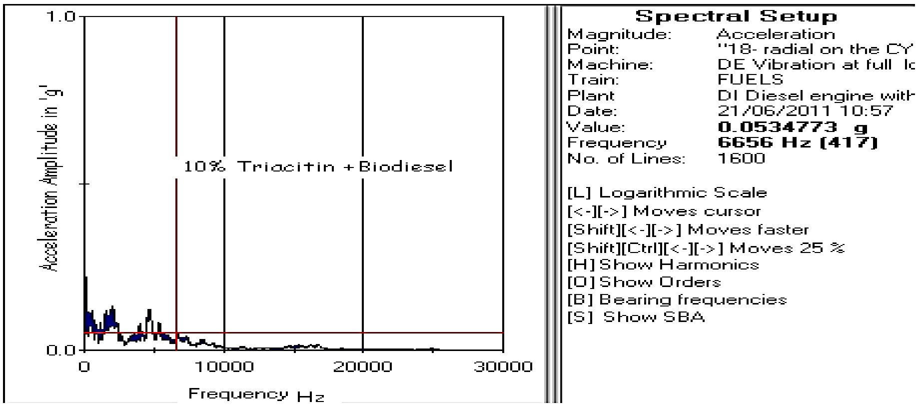


Spectral Setup

Magnitude:	Acceleration
Point:	"18- radial on the CY
Machine:	DE Vibration at full l
Train:	FUELS
Plant	DI Diesel engine wit
Date:	20/06/2011 12:18
Value:	**0.0802811 g**
Frequency	**6704 Hz (420)**
No. of Lines:	1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S] Show SBA

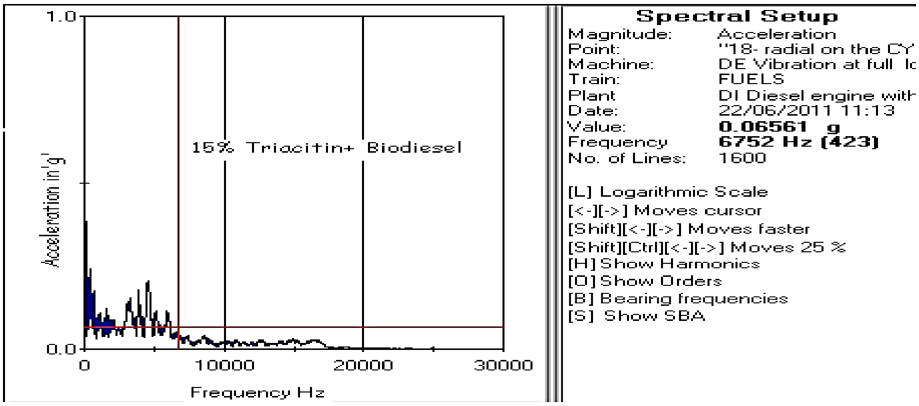
Fig. 13 FFT spectrum indicating *Knocking frequency* and the acceleration amplitude for 5% Triacetin- Biodiesel Blend application. Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.



Spectral Setup
Magnitude: Acceleration
Point: ''18- radial on the CY
Machine: DE Vibration at full lc
Train: FUELS
Plant DI Diesel engine witt
Date: 21/06/2011 10:57
Value: **0.0534773 g**
Frequency **6656 Hz (417)**
No. of Lines: 1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S] Show SBA

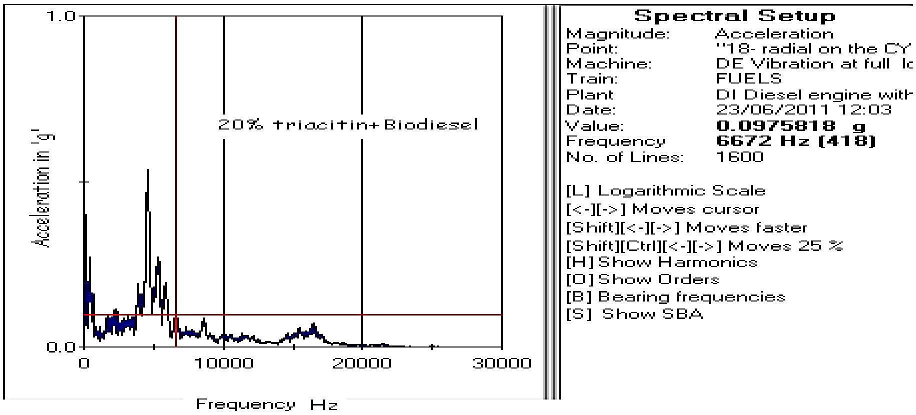
Fig. 14 FFT spectrum indicating *Knocking frequency* and the acceleration amplitude for 10% Triacetin- Biodiesel Blend application. Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.



Spectral Setup
Magnitude: Acceleration
Point: ''18- radial on the CY
Machine: DE Vibration at full lc
Train: FUELS
Plant DI Diesel engine witt
Date: 22/06/2011 11:13
Value: **0.06561 g**
Frequency **6752 Hz (423)**
No. of Lines: 1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S] Show SBA

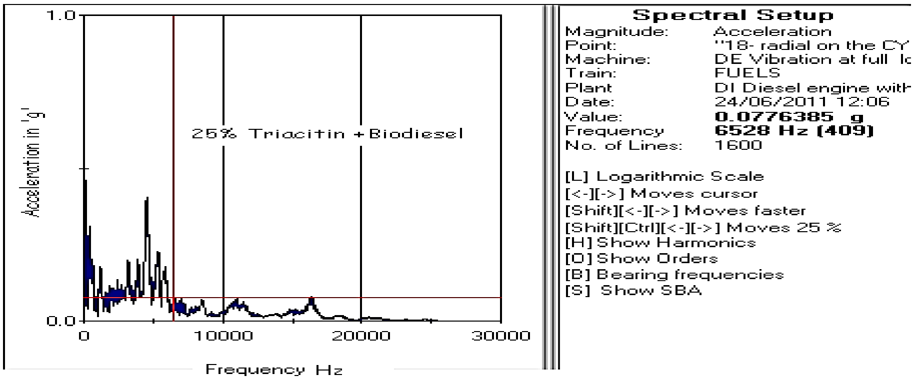
Fig. 15 FFT spectrum indicating *Knocking frequency* and the acceleration amplitude for 15% Triacetin- Biodiesel Blend application Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.



Spectral Setup
Magnitude: Acceleration
Point: ''18- radial on the CY
Machine: DE Vibration at full lc
Train: FUELS
Plant DI Diesel engine witt
Date: 23/06/2011 12:03
Value: **0.0975818 g**
Frequency **6672 Hz (418)**
No. of Lines: 1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S] Show SBA

Fig. 16 FFT spectrum indicating Knocking frequency and the acceleration amplitude for 20% Triacetin- Biodiesel Blend application Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.



```
Spectral Setup
Magnitude:        Acceleration
Point:            ''18- radial on the CY
Machine:          DE Vibration at full
Train:            FUELS
Plant             DI Diesel engine with
Date:             24/06/2011 12:06
Value:            0.0776385  g
Frequency         6528 Hz (409)
No. of Lines:     1600

[L] Logarithmic Scale
[<-][->] Moves cursor
[Shift][<-][->] Moves faster
[Shift][Ctrl][<-][->] Moves 25 %
[H] Show Harmonics
[O] Show Orders
[B] Bearing frequencies
[S]  Show SBA
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Fig.17 FFT spectrum indicating *Knocking frequency* and the acceleration amplitude for 25% Triacetin- Biodiesel Blend application. Vibration Measurement is made in the radial direction of the cylinder in line crank shaft axis.

5. Conclusion

1. Reducing overall calorific value of the fuel by replacing bio-diesel with Triacetin additive, which is Cetane improver, has reduced NO emissions to reasonable extent. Hence by this additive application, the only set back like excess NO_x with the neat bio-diesel application can be contained.

2. There is no trade off between HC and NO emissions in blending biodiesel with additive.

3. There is general decrease in engine smoke when additive blends have been applied. This may be because of the reduction in carbon molecules in the blends applied.

4. For this particular engine cylinder dimensions, the knocking frequency can be calculated taking into consideration the overall combustion temperature as 2000 ^{0}C. The knocking level can be assessed from the FFT graphs obtained by the engine vibration recorder. The readings on the cylinder head in radial direction in line crank axis have been chosen to quantify the amplitudes at knocking frequencies. It is understood that 10% blend of Triacetin produced lowest amplitude at the knocking frequency around 6,500Hz. Slight changes in the combustion temperatures may have altered the knocking frequencies by smallest margin around 6,500 Hz.

5. The blends with Triacetin produced the mean effective pressures lesser than 6.5 bar eliminating them in the knocking zone. 10% Triacetin blend, even though produced 7.2 bar IMEP, can be regarded as safe marginally below the IMEP ranges of diesel and biodiesel in the 80% burnt mass fraction zone and at 1500 rpm.

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