

COMBUSTION HEAT RELEASE RATE ANALYSIS OF C.I. ENGINE WITH SECONDARY CO-INJECTION OF DEE-H₂O SOLUTION - A VIBRATIONAL APPROACH

Y. V. V. SATYANARAYANA MURTHY, R. RAJESWARA REDDY

Mechanical Engineering Department, Gitam University, Visakhapatnam, India

*Corresponding Author: yedithasatyam@gmail.com

Abstract

This paper discusses the combustion propensity of single cylinder direct injection engine fueled with palm kernel methyl ester (PKME), which is non-edible oil and a secondary co-injection of saturated Diethyl ether (DEE) with water. DEE along with water is fumigated through a high pressure nozzle fitted to the inlet manifold of the engine and the flow rate of the secondary injection was electronically controlled. DEE is known to improve the cold starting problem in engines when used in straight diesel fuel. However, its application in emulsion form is little known. Experimental results show that for 5% DEE-H₂O solution injection, occurrence of maximum net heat release rate is delayed due to controlled premixed combustion, which normally helped in better torque conversion when the piston is in accelerated mode. Vibration measurements in the frequency range of 900Hz to 1300Hz revealed that a new mode of combustion has taken place with different excitation frequencies.

Keywords: Diesel engine, Diethyl ether, Ethanol, Heat release rate, Noise, Palm Kernel methyl ester.

1. Introduction

Water in fuel is a widely adopted technique to reduce engine emissions. However, direct injection of fixed percentage of water into the engine irrespective of the engine load will lead to increased HC and CO emissions and increased brake specific fuel consumption [1]. Direct injection of oil emulsions into the engine is often adopted to control the diesel engine emissions. Water-Diesel emulsion could reduce the NO_x and smoke levels without much change in brake thermal efficiency. The major drawback of water-fuel emulsion is its tendency to form air bubbles leading to changes in fuel injection timings and poor engine performance [2]. Hence, addition of DEE together with diesel-water emulsion could reduce both

Nomenclatures

<i>CHRR</i>	Cumulative heat release rate
<i>DEE</i>	Diethyl Ether
dm_i	Mass transfer at inlet
dQ	Amount of Heat transfer
dQ_{ch}	Heat released due to chemical energy
dQ_{ht}	Convection heat transfer
dU	Change in internal energy
dW	Amount of Work done
<i>FFT</i>	Fast Fourier Transform
h_i	Enthalphy change at inlet
<i>NHRR</i>	Net heat release rate
<i>PKME</i>	Palm Kernel Methyl Ester
<i>SFC</i>	Specific fuel consumption
T'	Temperature of the gas flow out of the crevice volume
T_w	Wall temperature
V_{cr}	Crevice Volume

both NO_x and HC emissions [3]. It has been shown that blends of DEE led combustion and proceeded further toward completion than ethanol [4], the other commonly added additive. The addition of DEE to biodiesel blends showed an improvement in the efficiency of the engine and reduced NO_x , HC and BSFC [5, 6, 7, 8]. It was reported that blends of DEE in POME (palm oil methyl ester) resulted in an improvement in acid value, viscosity, density and pour point with increasing content of DEE, accompanied by a slight decrease in energy content of biodiesel [9].

However, the use of biodiesel as fuel increases vibrations in the engine [10] when compared to conventional diesel fuel and certain biodiesel blends produce more vibration over others. The reason for this increase in vibrations might be the engine miss-firing and knocking at higher bio-diesel portions [11]. A variety of signal processing methods like statistical methods, wavelet analysis, FFT analysis etc., are being used to analyze the engine noise caused by vibration [12, 13]. The noise sources of the engine are being identified by independent component analysis which decomposes the measured signal into a number of independent components. This technique helps to identify and study the noise source of individual components and wavelet transform is then applied to represent the individual component in the time frequency domain. Combining continuous wavelet transform and individual component analysis, low level frequencies which are generally dominated by the engine firing frequency can be identified [14]. Some researchers developed techniques to study and analyze vibrations in engines [15, 16, 17]. Some researchers studied the effect of biodiesel blends on engine vibrations. Heidary et al. [18] has shown that biodiesel blends have a significant effect of engine vibrations and that the magnitude of vibration acceleration in vertical axis was more than that in the other two axes and magnitude of vibration acceleration in the longitudinal axis was more than that in the lateral axis. The fact that different biodiesel blends result in different values of vibration was corroborated in a later study [10].

In one of the author's earlier work [19], knock detection and engine performance on single cylinder DI- diesel engine was evaluated using pure

vibration signature analysis. However, pure water was used instead of a blend and performance characteristics such as engine pressure, combustion heat release rate and net heat release rate were not studied. In that study, it was proven that the injection of water has resulted in longer time duration of combustion during firing stroke. In a more recent study by the author [20], engine performance using pure diesel and biodiesel as fuel with secondary injection of H₂O-DEE was studied. Engine performance characteristics such as brake specific fuel consumption, brake thermal efficiency and emission characteristics such as release of un burnt hydrocarbons, NO_x, CO, CO₂, O₂, exhaust gas temperatures, smoke etc were studied. It was concluded that mass flow rate of 5% vol. H₂O – DEE solution is beneficial in view of emission performance, especially on NO emissions. However, vibration analysis was not performed in that study. Hence, a combination of engine performance using both engine studies and vibration studies seemed relevant in establishing the optimum performance characteristics.

In the current work, vibration studies along with engine performance studies were conducted on single cylinder DI engine fuelled with palm kernel methyl ester (PKME) with dual injection of DEE-H₂O solution. The measured vibration signal recorded was converted into FFT form. The time waveforms were presented in graphic form and the combustion mode due to the secondary co-injection of DEE-H₂O was studied.

2. Heat Release Rate Calculation

In-cylinder pressure and crank angle signals were obtained from the engine data logger for the load defined and stored on a high speed computer based digital data acquisition system. The data was recorded for 100 cycles. After obtaining the data for 100 cycles, the net heat release rate was calculated based on the first law of thermodynamics by taking the average value of pressure crank angle data. The present approach was to regard the cylinder contents as a *single zone*, whose thermodynamic state and properties were modeled as being uniform throughout the cylinder and represented by average values. No spatial variations were considered, so the model was said to be zero-dimensional. Equation (1) was used to model the single zone based on the 1st law of thermodynamics.

$$dU = dQ - dW + \sum_i h_i dm_i \quad (1)$$

2.1. Chemical Energy Released Calculation

The chemical energy released during combustion is calculated using Equation (2), where dQ_{ch} is the heat released due to chemical energy, dQ_{ht} is the convection heat transfer, V_{cr} the crevice volume, T_w is the wall temperature and T' is the temperature of the gas flow out of the crevice volume. This ordinary differential equation can easily be solved numerically for the net heat-release trace, if a cylinder pressure trace is provided, together with an initial value for the heat release.

$$\begin{aligned} dQ_{ch} &= \frac{1}{\gamma-1} V dp + \frac{\gamma}{\gamma-1} p dV + dQ_{ht} + \left(c_v T + RT' \left(1 + \frac{1}{\gamma-1} \right) \right) \frac{V_{cr}}{RT_w} dp \\ &= \frac{1}{\gamma-1} V dp + \frac{\gamma}{\gamma-1} p dV + dQ_{ht} + \left(\frac{1}{\gamma-1} T + T' \left(1 + \frac{1}{\gamma-1} \right) \right) \frac{V_{cr}}{T_w} dp \end{aligned} \quad (2)$$

3. Experimental Setup

A four stroke, direct injection, naturally aspirated single cylinder diesel engine was employed for the present study whose details are given in Table 1. The maximum solubility of DEE in water is 50ml/lit and the percentage of DEE blended in water is around 5% vol/wt basis. This Water-DEE (DEE-H₂O) solution was injected at the suction end at a pressure of 3 kgf/cm². The injection was controlled electronically by a controlled injection pump designed with suitable hardware, and it was timed to inject after the suction valve is fully opened. This DEE-H₂O solution is injected at 5%, 10%, 20%, 30% and 40% of the volume of the diesel injected. The load on the engine can be changed with the dynamometer control panel. Full load on the engine is equal to 40 kg on the spring balance. This dynamometer is popular for its stable and consistent readings even in the case of minor variation in engine speed and engine vibration. The tests were conducted at the rated speed of 1500 RPM at different loads of 0 kg, 10 kg, 20 kg, 30 kg, and 40 kg measured in the spring balance.

Table 1. Test Model Specifications and Test Conditions.

Feature	Specification
Type	4S, Single cylinder, compression ignition engine
Make	Kirloskar AV-1
Rated power	3.7kW
Bore/Stroke	80 mm/110 mm
Compression ratio	16.5:1
No. of Cylinders	1
Cylinder Capacity	624cc
Dynamometer	Electrical AC Dynamometer
Pressure (piezo sensor)	2000psi
Injection pressure	210bar

The engine was run with neat diesel and then with neat PKME while the secondary injection of DEE-H₂O solution was injected at the suction end with different mass flow as indicated above. Engine tests were run on the same engine and on same day for both diesel and PKME for each load, in order to have almost the same atmospheric conditions. The cooling water temperature was maintained constant (60°C to 65°C). All observations recorded were replicated thrice to get a reasonable value. Engine cylinder vibration in FFT form was monitored at each load and for each ester simultaneously in order to compare the cylinder excitation frequencies with the base line frequencies using diesel oil. Time wave forms on the cylinder head are also recorded to analyze the combustion. Since the very combustion in the cylinder is the basic exciter, the vibration study of the engine cylinder through the measured FFT and time waveforms are the representatives of combustion propensity. Vibration accelerometer was mounted on the cylinder head, preferably on the bolt connecting the head and the cylinder to record the engine vibrations using DC-11 data logger which directly gives the spectral data in the form of FFT, the overall vibration levels. This FFT data recorded was collected by On-Time Windows based software. The Time waveforms are obtained on the cylinder head by DC-11 in the OFF-ROUT mode and are presented in graphic form by Vast-a doss based software.

Four strategic points on the engine cylinder body and the foundation were chosen to assess the engine vibration. These four points are i) Vertical on top of

the cylinder head, ii) radial on the cylinder and parallel to the axis of the crank shaft, iii) radial on the cylinder and perpendicular to the axis of the crank shaft, iv) on the engine foundation. The vibration data recorded at these four points encompasses the engine vibration in the vertical direction, the two horizontal directions and the vibration transmitted to the foundation respectively. The vibration data was recorded with the help of an accelerometer. The schematic of the test setup is shown in Fig. 1. The experimental data generated for pressure vs. crank angle, cumulative heat release rate (CHRR) and Net heat release rate (NHRR) were documented and presented here using appropriate graphs. These tests are aimed at optimizing the injection of percentage of DEE-H₂O solution for long-term engine operation. The results are compared with the characteristics of 100% neat diesel oil fuelled engines as well PKME.

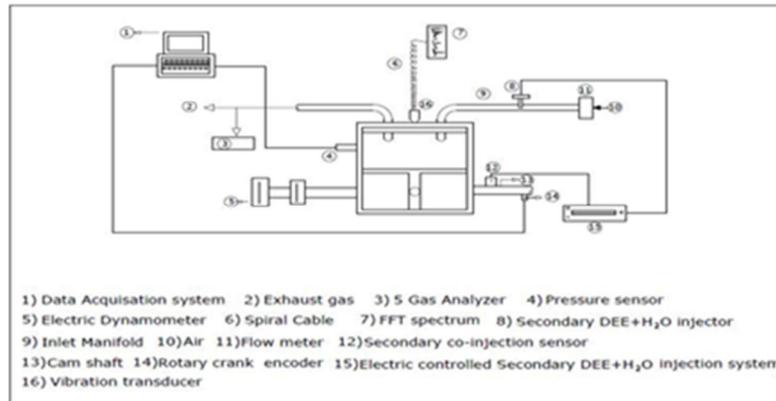


Fig. 1. Schematic Layout of Experimental Setup.

4. Results and Discussion

Figure 2 shows the comparison of peak pressures of neat diesel and biodiesel (PKME) with dual injection of DEE-H₂O solution ranging from 5% to 40% by volume compared to neat diesel injection under 0.50 of full load. The maximum peak pressure of neat diesel is 58 bar which is higher than that of biodiesel. Biodiesel has a proven history of having lower ignition delay when compared to neat diesel. The DEE-H₂O injection delayed the combustion as can be seen from Fig. 2. The peak pressure occurrence is also delayed, which is consistent with the amount of DEE-H₂O solution injected at suction. The peak pressure values also reduced with respect to the quantity of DEE-H₂O solution injected [21].

Figure 2 shows that there is a highest rise in peak pressure and decrease in expansion pressure for 20% DEE-H₂O solution. This sharp rise in pressure is due to the heat released in premixed combustion by DEE which dominates the heat released by the PKME. Figures 3 and 4 show that with the increase in load, there is a decrease of peak pressure rise with increase in percentage of DEE-H₂O solution except for 5% DEE-H₂O. Therefore, more burning occurs in the diffusion-burning phase rather than in the premixed phase [22]. The peak pressure mainly depends on premixed combustion. DEE, due to its low boiling point and flash point, auto-ignites during the compression stroke causing better air entrainment causing micro explosions. The latent heat of vaporization of water is

absorbed during the combustion of main fuel PKME keeping the cylinder temperature lower creating cooler combustion. Due to this, premixed combustion is improved and better diffused combustion takes place with betterment of torque.

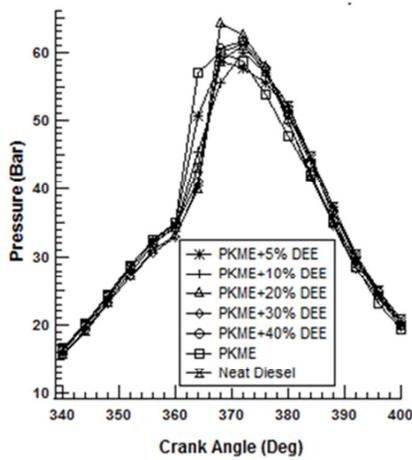


Fig. 2. Pressure vs. Crank Angle for $\frac{1}{2}$ full load condition.

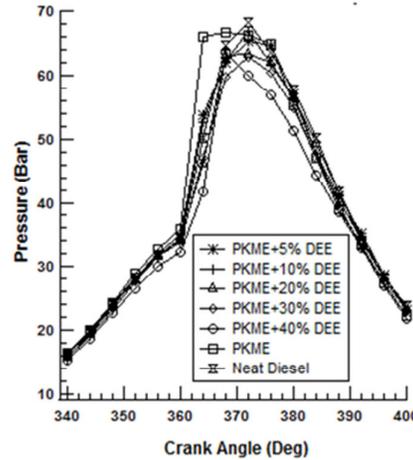


Fig. 3. Pressure vs. Crank Angle for $\frac{3}{4}$ full load condition.

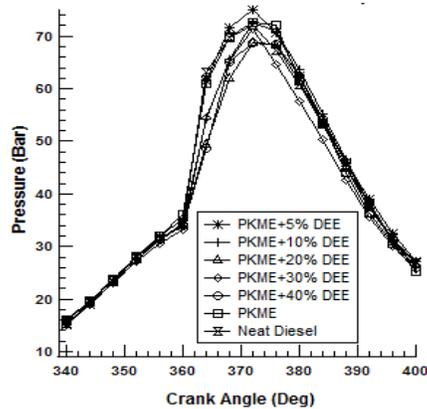


Fig. 4. Pressure vs. Crank Angle for full load condition.

4.1. Combustion heat rate analysis

The variation of heat release rate for different percentages of DEE-H₂O injections under varying load conditions is seen in Figs. 5 through 8. The heat release rate mainly depends on ignition delay and injection timings. At $\frac{1}{4}$ th full load condition, the heat release rate is more for diesel than for the biodiesel PKME due to the lower heating value of biodiesel than neat diesel. Figure 5 shows that 5% DEE-H₂O

injection has a higher heat release rate because, at part loads, the gas temperature inside the engine is low and hence, accumulation of more PKME in premixed zone has taken place due to which the heat release rate is increased. Figure 6 shows that 20% DEE- H₂O injection has higher heat release rate at half full load due to the increase in ignition delay. This may be due to the poor vaporization of 20% DEE-H₂O solution. At higher loads, premixed combustion is decreased with simultaneous improvement in diffused combustion as observed for 5% DEE-H₂O solution. This is due to the complete burning of DEE which creates micro explosions in the solution leading to improve the swirl in the combustion chamber, due to which the ignition delay is decreased and higher heat is released, which can be seen in Figs. 7 and 8.

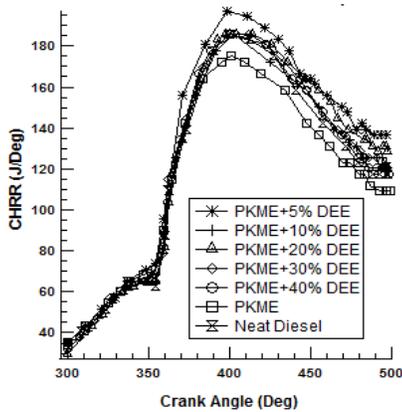


Fig. 5. CHRR vs. Crank Angle for 1/4 full load condition.

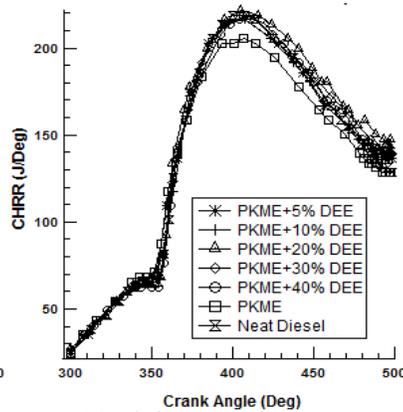


Fig. 6. CHRR vs. Crank Angle for 1/2 full load condition.

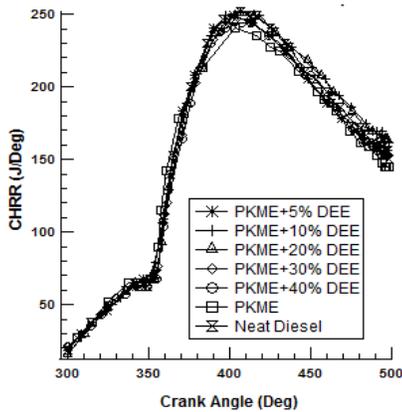


Fig. 7. CHRR vs. Crank Angle for 3/4 full load condition.

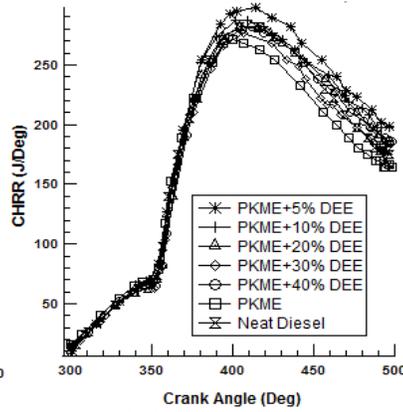


Fig. 8. CHRR vs. Crank Angle for full load condition.

Figures 9 through 13 show the variation of net heat release rate with increase in load for different percentages of DEE-H₂O injection timings. In Fig. 9, the net heat release rate starts decreasing with increase in the quantity of DEE-H₂O solution under no load conditions. We find that under no load conditions, 5% DEE-H₂O solution exhibits higher peak of heat release rate in premixed

combustion period, and the curve sharply falls down in the diffused and after combustion period, indicating decrease in thermal efficiency and increase in brake specific fuel consumption [23].

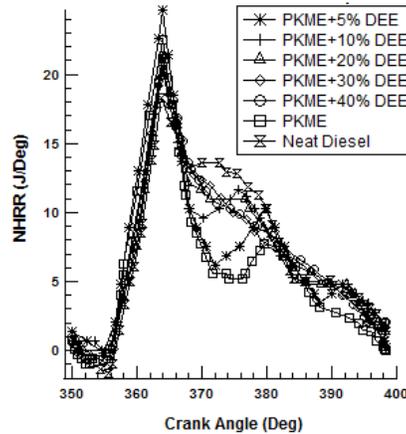


Fig. 9. NHRR vs. Crank Angle for no load condition

The start of combustion for the same injection timing was observed to be delayed indicating an increase in the ignition delay with 5% DEE-H₂O solution. This leads to larger accumulation of the fuel in the ignition delay period and leads to rapid combustion of more amount of fuel in the premixed part than the diffused part.

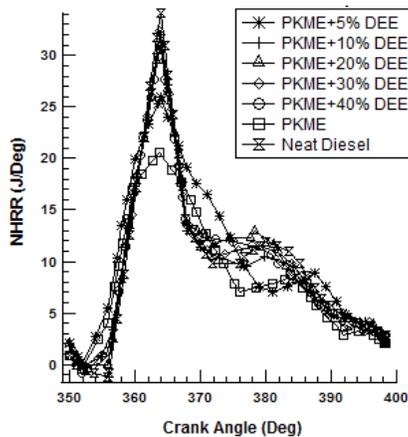


Fig. 10. NHRR vs. Crank Angle for 1/4 full load condition.

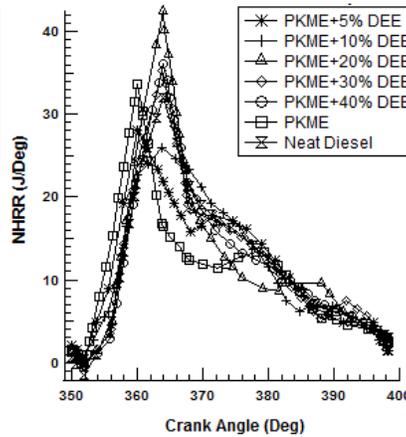


Fig. 11. NHRR vs. Crank Angle for 1/2 full load condition.

When the load on the engine increases, improvement of peak heat release rates of all percentages of DEE-H₂O injection for the same start of injection timing is observed (Figs. 10 through 13). Premixed combustion is more

prominent than the diffused combustion for higher loads for all percentages of DEE-H₂O injection except for 5% DEE-H₂O injection. Figs. 12 and 13 show that there is a decrease in intensity of premixed combustion for 5% DEE-H₂O injection. At 3/4th full load and full load conditions, intensity of premixed combustion is well controlled for 5% DEE-H₂O injection with the increased area under the secondary peak, thus resulting in better torque conversion during the piston slap mode.

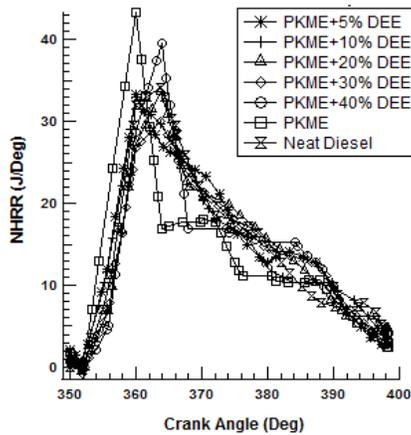


Fig. 12. NHRR vs. Crank Angle for 3/4 full load condition.

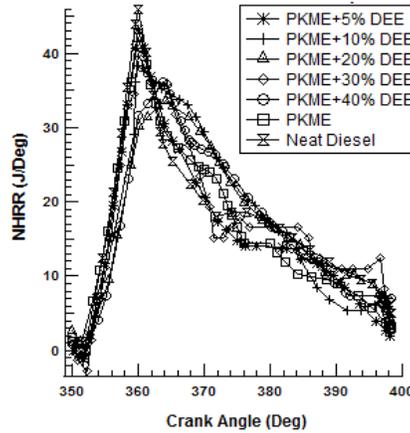


Fig. 13. NHRR vs. Crank Angle for full load condition.

Finally, the results obtained are summarized in terms of peak values obtained for pressure, CHRR and NHRR for different blends at different loads. Figures 2 to 13 show the changes in properties over crank angle. However, the results can be better visualized by plotting the peak values obtained as shown in Figs. 14, 15 and 17. Figure 14 shows the peak pressure obtained at various loads. While comparing the values of peak pressure of various biodiesel blends with neat diesel, it can be observed that neat diesel has the lowest desired peak pressure only at no load condition. At various load levels, atleast some of the biodiesel blends performed better (lower peak pressure) than neat diesel. However, there is little variation among all the fuels and there is no conclusive evidence as to which biodiesel blend performs best in terms of peak pressure. When comparing CHRR values from Fig. 15, it is clear that pure PKME always had lower CHRR values than neat diesel. However, with the addition of DEE, the biodiesel matched the maximum value of CHRR in almost all the cases. The highest values of CHRR were obtained at lower concentrations of DEE (5%, 10% and 20%) as compared to higher concentrations (30 and 40%). Rao et al. [24] reported the best values of peak pressure and heat release rate at 10% additive among 5, 10, 15, 20 and 25% concentrations. However, they used coconut biodiesel with triacetin (cetane improver) additive blends. NHRR values for various fuels also do not show a clear trend. However, it can be seen that some biodiesel blends perform sufficiently close to neat diesel.

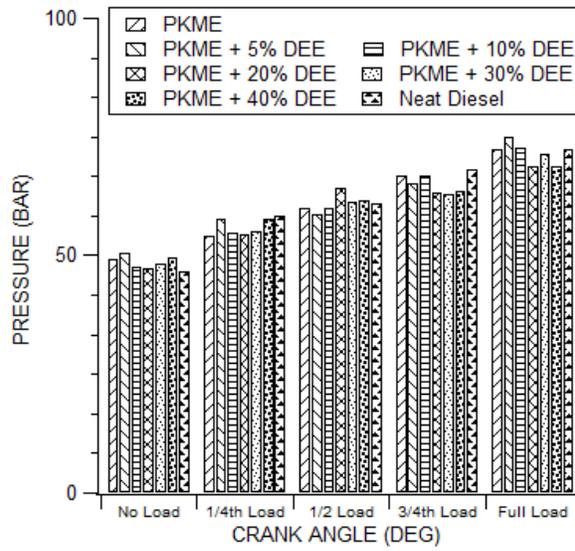


Fig. 14. Peak pressures for different biodiesel blends at different loads.

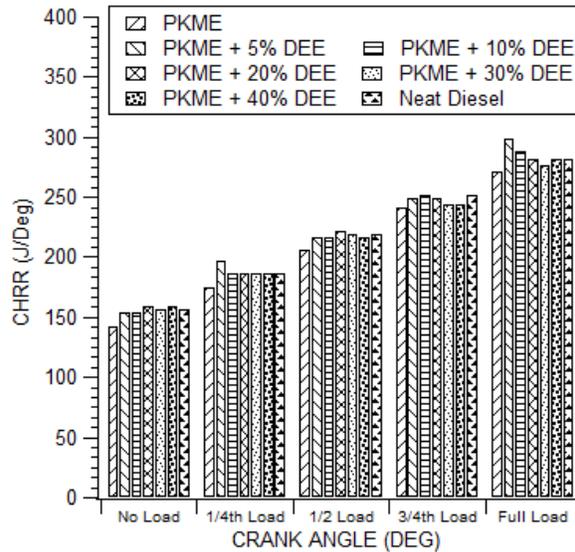


Fig. 15. Maximum CHRR values for different biodiesel blends at different loads.

Kannan et al. [25] reported that 20% DEE additive outperformed other concentrations (5, 10, 15 and 20%) when used with Thevetia peruviana biodiesel. Ramesh Babu et al. [26] used DEE mixed with the MME (Mahua methyl ester) at different proportion of 3%, 5%, 10% and 15% and reported significant reduction in NO_x emissions especially for DEE addition of more than 10% and substantial smoke reduction with 15% DEE. Martin et al. [27]

also reported that the addition of small quantities of DEE to cotton seed oil (CSO) improved the performance of the diesel engine. When algal oil methyl ester and its blends are used as a fuel, the best injection timing was found to be 340 crank angle degree with optimum performance, better combustion characteristics and minimal emission [28]. In this work, optimum performance was obtained between 360° and 400°. Looking at the results of various researchers, it can be conclusively stated that biodiesel and biodiesel blends perform well enough to warrant more research.

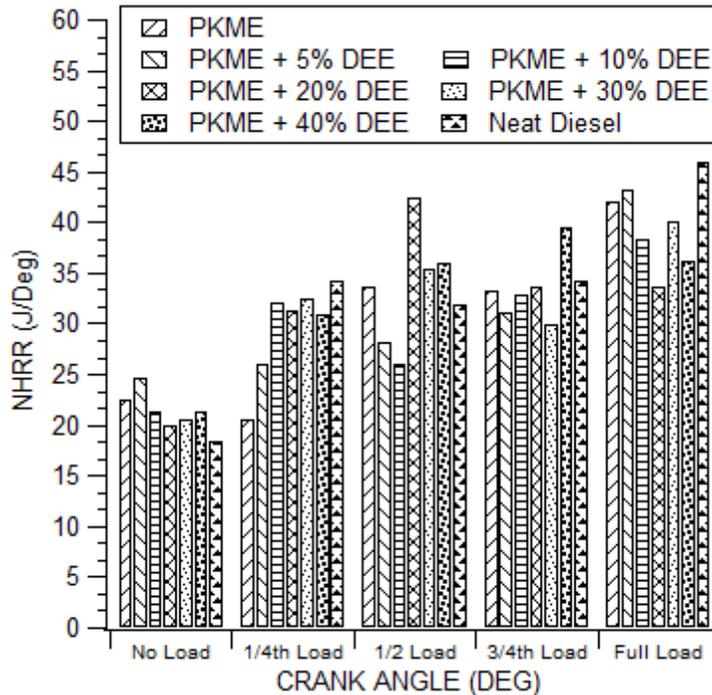


Fig. 16. Maximum NHRR values for different biodiesel blends at different loads.

4.2. Vibration analysis

The vibration studies indicate that there is a tradeoff between the vibrations recorded in different directions on the cylinder head. There is also a tradeoff between the cylinder head vibration and the engine foundation vibration. It can be observed from Figs. 17 and 18, for 5% DEE-H₂O injection there is an increase of vibration from cylinder head to the foundation. Since the spectrum recorded on the cylinder head is the representative of the combustion inside the cylinder, it can be assessed that a new mode of combustion has taken place with different excitation frequencies in the presence of DEE-H₂O solution.

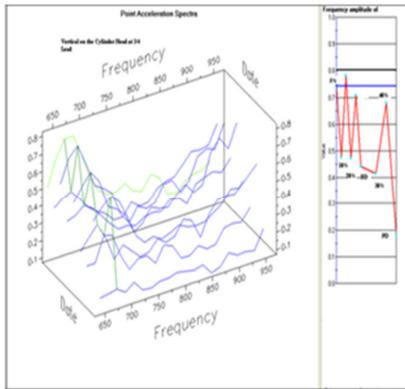


Fig. 17. Spectrum on cylinder head at 3/4th full load for PKME+5% DEE-H₂O solution.

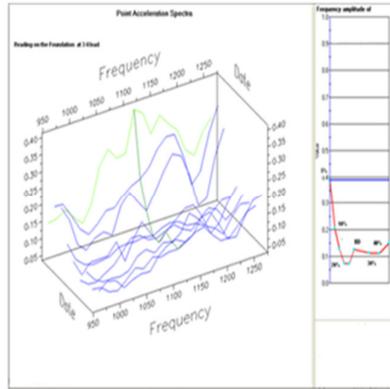


Fig. 18. Spectrum on engine foundation at 3/4th full load for PKME+5% DEE-H₂O solution.

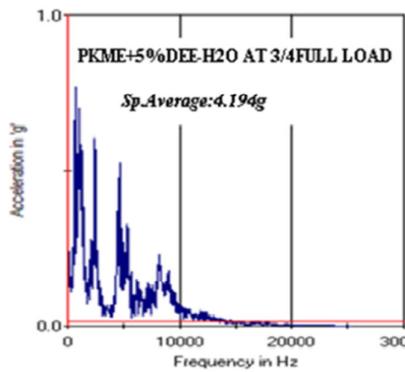


Fig. 19. FFT Spectrum for PKME + 5% DEE+H₂O solution.

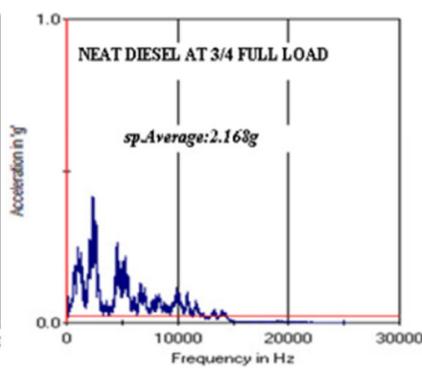


Fig. 20. FFT Spectrum for Neat Diesel.

Figures 19 and 20 show the FFT spectrum under 3/4 full load condition for PKME and for neat diesel operation respectively. Additional frequencies are observed in the spectrum for PKME operation with 5% DEE-H₂O solution and this can be tallied from the graphs in Figs. 19 and 20.

Table 2. Average Spectrum values on cylinder head for PKME + 5% DEE+H₂O solution.

Load	Average Spectrum Value recorded vertical on cylinder head
Zero Load	2.017 g
1/4 th full load	2.600 g
1/2 full load	3.597 g
3/4 th full load	4.194 g
Full load	3.840 g

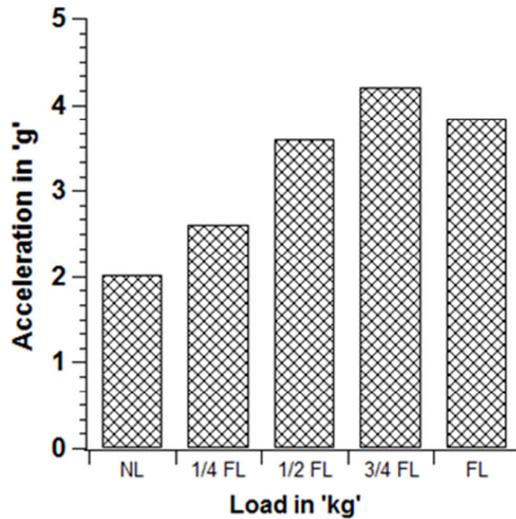


Fig. 21. Average accelerations at various loads recorded vertical on cylinder head.

Table 2 and Fig. 21 show the average spectrum values recorded on the cylinder head at various loads for PKME + 5% DEE-H₂O solution. The spectrum average value recorded for PKME + 5% DEE-H₂O under 3/4 load condition is 4.194 g (Fig. 19) but for neat diesel operation it is only 2.168 g (Fig. 20). This is because of better combustion due to the enhanced swirl created by complete vaporization of DEE-H₂O solution leading to complete lean combustion. It was observed that there is an increase in vibration from the cylinder head to the engine foundation with higher injection rates of DEE-H₂O solution. The DEE-H₂O solution has created split frequency combustion in the range defined i.e. at 10,000 Hz. 3D graphs have been drawn for different ranges of frequencies and the instant amplitudes in that duration for different DEE-H₂O solution ratings have been studied. It is observed that with the increase in the percentage of DEE-H₂O solution, the vibration values have decreased as can be observed from the 3-D graphs from Fig. 14 and Fig. 15. On most occasions, the neat diesel has produced lower values of vibration comparatively at all loads. Fig. 14 depicts that in the crucial frequency range of 650-700Hz, the amplitude raise is abnormal to the tune of 0.8 g at 3/4 full load of the engine for 5% DEE-H₂O injection. This can be attributed to better torque conversion at this percentage and also the average spectrum value at this percentage is 4.194 g, which is also an indication of better torque conversion.

Higher vibration levels on the foundation of the engine depend on the modal vibration of the structure for a particular kind of excitation during combustion which changes with the kind of fuel used. The vibration in the direction of piston slap and the vibration transmitted to the foundation of the engine are usually complementary. Higher torque conversion normally creates more vibration isolation at the foundation. 5% DEE-H₂O solution is one such combination which delivered less vibration at engine foundation. The time

waves depicted in Fig. 22 through Fig. 24 indicate longer time duration of combustion during firing stroke in the case of injection of DEE-H₂O solution. But time wave form of 5% DEE-H₂O solution is similar to that of the time wave recorded with neat diesel run at full load.

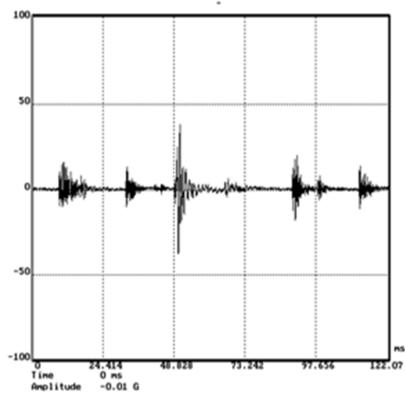


Fig. 22. Time wave form for Neat Diesel (recorded on cylinder head at full load).

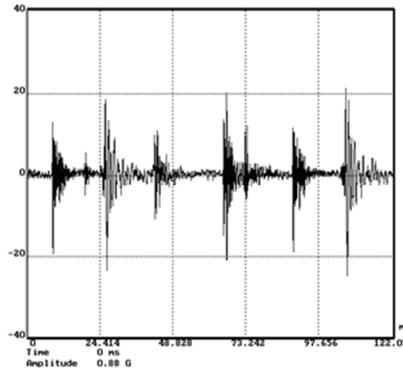


Fig. 23. Time wave form for PKME (recorded on cylinder head at full load).

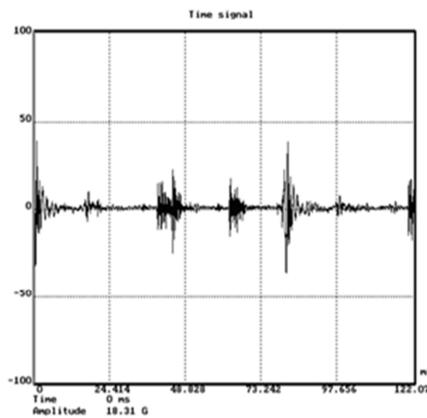


Fig. 24. Time wave form for PKME + 5% DEE + H₂O (recorded on cylinder head at full load).

5. Conclusions

Experimental work on single cylinder direct ignition engine with palm kernel methyl ester (PKME) as fuel with secondary co-injection of DEE-H₂O solution is conducted and the following conclusions are drawn.

- At higher loads, premixed combustion is decreased with simultaneous improvement in diffused combustion for 5% DEE-H₂O solution. This is due to the complete burning of DEE which creates micro explosions in the solution,

leading to improvement of the swirl in the combustion chamber, due to which the ignition delay is decreased and higher heat is released.

- Premixed combustion is more prominent than the diffused combustion for higher loads for all percentages of DEE-H₂O injection except for 5% DEE-H₂O injection.
- There is a decrease in intensity of premixed combustion for 5% DEE-H₂O injection at 3/4th full load and full load conditions. Intensity of premixed combustion is well controlled for 5%DEE-H₂O injection with the increased area under the secondary peak, resulting in better torque conversion during the piston slap mode.
- For 5% DEE-H₂O injection, there is an increase in vibration from the cylinder head to the engine foundation from no load condition to ¾ full load except for full load condition. However it is always advisable that engine should run at load lesser than the full load conditions.
- The combustion pattern has changed with the injection of DEE-H₂O solution.
- The vibration spectrum was analyzed for the frequencies up to 10,000Hz. Addition of DEE in water has created a change in vibration spectrum and a split frequency was observed in the frequency range of 10000 Hz. It has been observed from the 3-D graphs that with the increase in the percentage of DEE-H₂O solution, the vibration values have decreased.
- In the critical low frequency range of 650-700Hz, the amplitude rise is abnormal to the tune of 0.8 g at 3/4 Full load of the engine for 5%DEE-H₂O injection. This can be attributed to better torque conversion at this percentage, and also the average spectrum value at this percentage is 4.194 g, which is also an indication of better torque conversion.
- There is a similarity of time wave forms for 5% DEE-H₂O and engine run on neat diesel run at full load condition.
- On the whole, the combustion analysis and vibration studies indicate that PKME with 5% DEE-H₂O secondary co-injection is the best combination.

References

1. Daly, D.T.; and Nag, P. (2001). Combustion modeling of soot reduction in diesel and alternate fuels using CHEMKIN. *SAE Technical Paper*, 2001-01-1239.
2. Lanzafame, R. (1999). Water injection effects in a single-cylinder CFR engine. *SAE Technical Paper Series*, 1999-01-0568.
3. Subramanian, K.A.; and Ramesh, A. (2002). Use of diethyl ether along with water-diesel emulsion in a DI-diesel engine. *SAE Technical Paper*, 2002-01-2720.
4. Mack, J.H.; Flowers, D.L.; Buchholz, B.A.; and Dibble, R.W. (2004). Investigation of HCCI combustion of diethyl ether and ethanol mixtures using Carbon 14 tracing and numerical simulations. *30th International Symposium on Combustion*, Chicago, Illinois.
5. Akshatha, D.S.; Manavendra. G.; and Kumarappa, S. (2013). Performance evaluation of Neem biodiesel on CI engine with diethyl ether as additive.

International Journal of Innovative Research in Science, Engineering and Technology, 2(8).

6. Pugazhivadivu, M.; and Rajagopan, S. (2009). Investigations on a diesel engine fuelled with biodiesel blends and diethyl ether as an additive. *Indian Journal of Science and Technology*, 2(5), 31-35.
7. Nagdeote, D.D.; and Deshmukh, M.M. (2012). Experimental study of diethyl ether and ethanol additives with biodiesel-diesel blended fuel engine. *International Journal of Emerging Technology and Advanced Engineering*, 2(3), 195-199.
8. Jegadheesan, C.; Somasundaram, P.; Meenakshipriya, B.; and Vignesh, U.P. (2013). Effect of DEE injection in Pongamia Pinnata biodiesel fuelled CI engine using hydrogen as secondary fuel. *Advanced Materials Research*, 768, 188-194.
9. Ali, O.M.; Mamat, R.; and Faizal, C.K.M. (2013). Effects of diethyl ether additives on palm biodiesel fuel characteristics and low temperature flow properties. *International Journal of Advanced Science and Technology*, 52, 111-120.
10. Taghizadeh-Alisaraei, A. (2012). Vibration analysis of a diesel engine using biodiesel and petrodiesel fuel blends. *Fuel*, 102, 414-422.
11. Manorathna, R.P.; and Nanayakkara, N.K.B.M.P. (2011). Experimental investigation of operating characteristics of bio-diesel on a conventional diesel engine. *International Journal of Innovation, Management and Technology*, 2(3), 199-203.
12. Ilic, Z.; Rasuo, B.; Jovanovic, M.; and Jankovic, D. (2013). Impact of changing quality of air/fuel mixture during flight of a piston engine aircraft with respect to vibration low frequency spectrum. *FME Transactions*, 41(1), 25-32.
13. Sitnik, L.; Magdziak-Toklowicz, M.; and Wrobel, R. (2011). Comparative analysis of the vibrations of a different kind of engine mounted in the same new motor vehicles. *Journal of KONES Powertrain and Transport*, 18(4).
14. Ramachandran, T.; and Padmanadhan, K.P. (2012). Review on Internal combustion engine vibrations and mountings. *IJESET*, 3(1), 63-73.
15. Klinchaeam, S.; Nivesrangsan, P.; and Lokitsangthong, M. (2009). Condition monitoring of a small four-stroke petrol engine using vibration signals. *KMITL Sci. Tech. Journal*, 9(1), 9-17.
16. Lus, T.; and Lutowicz, M. (2010). Marine diesel engines diagnostics. *Research papers of Lithuanian University of Agriculture*, 42(2-3), 141-149.
17. Chiatti, G.; Chiavola, O.; and Recco, E. (2013). Combustion and vibration characteristics in a small displacement diesel engine fuelled with biodiesel blends. *SAE Technical Paper*, 2013-01-1902.
18. Heidary, B.; Hassan-beygi, S.R.; Ghobadian, B.; and Taghizadeh, A. (2013). Vibration analysis of a small diesel engine using diesel-biodiesel fuel blends. *Agric Eng Int: CIGR Journal*, 15(3), 117-126.
19. Satyanarayanamurthy, Y.V.V. (2011). Combustion analysis and knock detection in single cylinder DI-diesel engine using vibration signature analysis. *International Journal of Engineering Science and Technology*, 3(1), 10-16.

20. Satyanarayanamurthy, Y.V.V. (2012). Experimental investigations of real time secondary co-injection of water-diethyl ether solution in DI-diesel engine fueled with palm kernel methyl ester. *Journal of Engineering Science and Technology*, 7(6), 711-721.
21. Abdalla, A.Y.; Radwan, M.S.; and Ahmed, S.H. (1991). Smoke level and operational roughness of a pre- combustion chamber diesel engine running on gasoil/methanol blends. *SAE Technical Paper*, 912358.
22. Devan, P.K.; and Mahalakshmi, N.V. (2009). Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels. *Fuel Processing Technology*, 90(4), 513-519.
23. Senthil Kumar, M.; Ramesh, A.; and Nagalingam, B. (2003). Use of hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine. *International Journal of Hydrogen Energy*, 28(10), 1143-1154.
24. Rao, P.V.; and Rao, B.V.A. (2012). Heat release rate calculations and vibration analysis of DI-diesel engine operating with coconut oil methyl ester-triacetin additive blends. *The IUP Journal of Mechanical Engineering*, 5(2), 43-57.
25. Kannan, T.K.; and Marappan, R. (2011). Effects of injection timing on the performance and emissions of a diesel engine fuelled with diethyl ether blended thevetia peruviana biodiesel. *International Journal of Energy Technology and Policy*, 7(5-6), 455-468.
26. Ramesh Babu, P.; Prasad Rao, K.; and Appa Rao, B.V. (2012). The role of oxygenated fuel additive (DEE) along with Mahuva methyl ester to estimate performance and emission analysis of DI-diesel engine. *International Journal of Thermal Technologies*, 2(1), 119-123.
27. Martin, M.L.J. (2012). A comparative analysis of different methods to improve the performance of cotton seed oil fuelled diesel engine. *Fuel*, 102, 372-378.
28. Hariram, V.; and Kumar. M.G. (2012). The Effect of injection timing on combustion, performance and emission parameters with AOME blends as a fuel for compression ignition engine. *European Journal of Scientific Research*, 79(4), 653-665.