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Experimental study on Combustion and Emission Characteristics of an Indirect Injection (IDI) Diesel Engine operated with Pongamia Methyl Ester and Isobutanol as an Additive

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Abstract— *In this study, experimental investigations have been carried out to examine the combustion, exhaust gas emission and cylinder vibration characteristics of an indirect injection (IDI) diesel engine. The engine was operated with five fuel samples of Pongamia Methyl Ester (PME) with Isobutanol (IB) as an additive. The samples are prepared by volume percentage basis. Engine tests were performed at five different engine loads ranging from no load to maximum load at fixed engine speed 1500 rpm. The results obtained with the fuel samples were compared to those obtained for the neat biodiesel and conventional diesel as a baseline fuel. Combustion pressure data was collected and the net and cumulative heat release rates have been derived to analyze combustion in the main combustion chamber. The net heat release rate curves for 6 percent isobutanol are almost flat with no sudden hikes in the heat release indicating smoother combustion. The cumulative heat release for the same percentage has an edge over the other fuel combinations showing better diffused combustion in the main chamber indicating maximum torque conversion. The exhaust gas emissions of the engine using 6 percent isobutanol in biodiesel were compared with conventional diesel fuel operation. The reduction percentages quantified are by 71 for HC, 0.02 for CO, 0.5 for CO2 and 31 for NO. The Fast Fourier Transformation signatures recorded vertical on the cylinder head and foundation indicate uniform amplitude modulation revealing smoother combustion for the 6 percent of additive in biodiesel. The time waves recorded on the cylinder head envisage better combustion in the main combustion chamber judicious combustion sharing in between chambers.*

Keywords—IDI engine, Pongamia methyl ester, Isobutanol, biodiesel, additive, Combustion pressure, exhaust gas emission, vibration.

I. INTRODUCTION

Diesel engines are widely used for transportation, automotive, agricultural applications and industrial sectors because of their high fuel economy and thermal efficiency. The existing diesel engines operate with conventional diesel fuel derived from crude oil. It is well known that the world petroleum resources are limited and the production of crude oil is becoming more difficult and expensive. At the same time, with the increasing concern about environmental protection and more stringent government regulation, the researches on the decreasing of exhaust emissions and improving fuel economy have become a major research issue in the engine combustion and development. A lot of research related to the emissions reduction has been performed by using biodiesel as alternative fuel. The studies related to the alternative fuels application should be pursued for diesel engines especially for indirect injection (IDI) diesel engines in view of certain advantages. Canakci et al. [1] experimentally investigated the combustion and exhaust emissions of a single cylinder diesel engine at three different injection timings when methanol/diesel fuel blends were used from 0 to 15%, with an increment of 5%. The results indicated that the P_{max} decreased and the ignition delay (ID) increased with the increase of methanol mass fraction at all injection timings. The increment in the ID led to the deterioration of combustion thereby reduced the P_{max}. Also advanced injection timing boosted the P_{max} and the rate of heat release because of the increase in ID. Huang et al. [2, 3] used the diesel/methanol blend and combustion characteristics and heat release analysis in a CI engine. According to the experimental results, the increase in methanol mass fraction in the diesel/methanol blends resulted in an increase in the heat release rate at the premixed burning phase and shortened the combustion duration of the diffusive burning phase.

Shi X et al. [4-6] studied the combustion characteristics, engine performance, and emissions of three-component fuel [croton oil (CRO), 1-butanol (BU), and diesel (D2)] blends. It is expected that the use of BU blended with vegetable oil and D2 may provide a solution for the phase stability problem of the vegetable oil-simple alcohol blends, improve combustion characteristics, and minimize emission problems related to the burning of petroleum diesel fuel in a diesel engine. Blend fuels follow a trend similar to that of diesel fuel: the peak heat release value increases as the load increases. It can be seen that the blends record an improvement in the heat release rate at the premixed combustion period. The presence of BU and oxygen in the blends decreases the cetane number (CN) of the blends and increases the ignition delay period. This is caused by high temperature and high cylinder pressure, better fuel-air mixing, and higher flame velocity associated with higher loads. A larger percentage of alcohol in the blend is the reason for slightly lower heat release rates at higher loads than that of the D2 sample because the samples containing alcohol recorded a low lower heat value (LHV). D2 exhibits the highest LHV value and lower viscosity: these two properties influence the heat release characteristics of the fuel.

In other studies, Rakopoulos C.D. et al. [7] investigated the effect of ethanol/diesel blends with 5%, 10% and 15% (by vol.) ethanol on the combustion and emissions characteristics of a high speed direct injection diesel engine. According to the experimental results, the ID for the E15 blend was higher than pure diesel fuel; also there was no significant difference among the Pmax for each load conditions. The combustion characteristics of IDI diesel engines are different from the DI diesel engines, because of greater heat-transfer losses in the swirl chamber. However, IDI diesel engines have a simple fuel injection system and lower injection pressure level because of higher air velocity and rapidly occurring air-fuel mixture formation in both combustion chambers of the IDI diesel engines. In addition, they do not depend upon the fuel quality and produce lower exhaust emissions than DI diesel engines [8]. Many studies have been conducted on the performance of and emissions from engines fueled with diesel–alcohol blends, [9 and 10] and most of these investigations have concentrated on methanol and ethanol. Compared with ethanol and methanol, butanol has many advantages. It has a higher energy density than those of ethanol and methanol. Butanol has a high cetane number which makes it more suitable as an additive to diesel fuel. n-butanol is much less hygroscopic than ethanol and methanol are, preventing it from water contamination. Butanol is less corrosive to the materials in the fuel delivery and injection system, which allows it to be used in the existing pipeline. However, few studies have reported results from using isobutanol–diesel blends in diesel engines. Blending isobutanol with diesel can maintain good stability for a long time without phase separation.

Chun and Kim [11] measured oscillations at the upper part of the cylinder block center for knock in SI (spark signal provided by an accelerometer placed externally. Othman [12] placed the accelerometer horizontally on the side wall of a SI engine to monitor the combustion anomalies like misfiring. Antoni et al. [13] used vibrations to indicate malfunctioning. Blunsdon and Dent [14] showed that varying the injection profile strongly affect the bulk motion settling inside the combustion chamber. The maximum amplitude of the vibration provides information about combustion intensity, high amplitude may indicate early ignition or presence of a large amount of fuel in the cylinder prior to ignition, lower amplitude may indicate late ignition, injection malfunction or engine compression malfunction. It has been proved by Carlucci et al. [15] that injection pressure and injected quantities, over an energy release threshold, really affect the vibration signals in a peculiar way; injection timing affects the engine block vibration in a less evident way. Gideon et al. [16] used vibration measurement to identify malfunctioning in a multi cylinder engine. In the area of DI diesel engine endeavors made to analyze engine vibration with the introduction of neat biodiesel and biodiesel with additives [17-19]. DI engines also reveal an economical point at which the engine vibrations are minimized.

In this study deals with finding the effect of Isobutanol additive in Pongamia Methyl Ester biodiesel on the engine combustion, emission and vibration characteristics of variable speed IDI engine. Experiments are conducted on indirect injection (IDI) diesel engine run at constant speed of 1500 rpm operated with five fuel samples of Pongamia Methyl Ester (PME) with Isobutanol (IB) as an additive. Engine tests were performed at five different engine loads ranging from no load to maximum load. The results obtained with the fuel samples were compared to those obtained for the neat biodiesel and conventional diesel as a baseline fuel. Pressure crank angle data has been obtained within one complete cycle of operation and the data is averaged over 6 cycles. But micro level investigation into one degree of crank revolution cannot be obtained since the least count of measurement is 10 only. An attempt is made to investigate the aspect of combustion within one degree by measuring the vibration data with a maximum range of 16,500 Hz which can probe into the happenings down to $6x10^{-2}$ millisecond. This can enable us to detect the detonation and knocking trends that happens at higher frequencies with the new fuels.

The vibration data is recorded with the help of an accelerometer analyzed graphically in acceleration, velocity and log-log modes.

II. EXPERIMENTATION

The experimental setup consists of the following equipments:

1. Single cylinder IDI diesel engine loaded with eddy current dynamometer.
2. Engine Data Logger (make: APEX INNOVATIONS)
3. Exhaust gas Analyzer (1600L, German make)
4. Smoke Analyzer (Diesel Tune 114)
5. DC-11 Vibration analyzer made in Canada.

The schematic diagram of the engine test bed is shown in Fig.1. Experiments were conducted with diesel, neat PME and Isobutanol (IB) in the biodiesel with different percentages i.e. 2%, 4%, 6%, 8% and 10%. Engine tests were performed at five different engine loads ranging from no load to maximum load at fixed engine speed 1500 rpm. Computer with C7112 software designed by “Apex Innovations”, Pune, India; Delta 1600-L exhaust gas analyzer (German Make) and DC-11 vibration analyzer made by DPL group, Canada were used to analyze the combustion, exhaust gas emissions and cylinder vibration characteristics.

The pressure transducer is fixed (flush in type) to the cylinder body (with water cooling adaptor) to record the pressure variations in the combustion chamber. Crank angle encoder sends signals of crank angle with reference to the TDC position on the flywheel and will be transmitting to the data logger. The data logger synthesizes the two signals and final data is presented in the form of a graph on the computer.

Exhaust gas analyzer is used to measure HC, CO, CO_2 and NO in exhaust gases at all loads and graphs are drawn to compare. The vibration analyzer is a digital spectrum analyzer and data collector specifically designed for machine condition monitoring, advanced bearing fault detection and measurement diagnostics. Three strategic points on the engine cylinder body and the foundation are chosen to assess the engine vibration. These three points are

i) Vertical on top of the cylinder head,
ii) Radial on the cylinder and perpendicular to the axis of the crank shaft,
iii) On Engine foundation

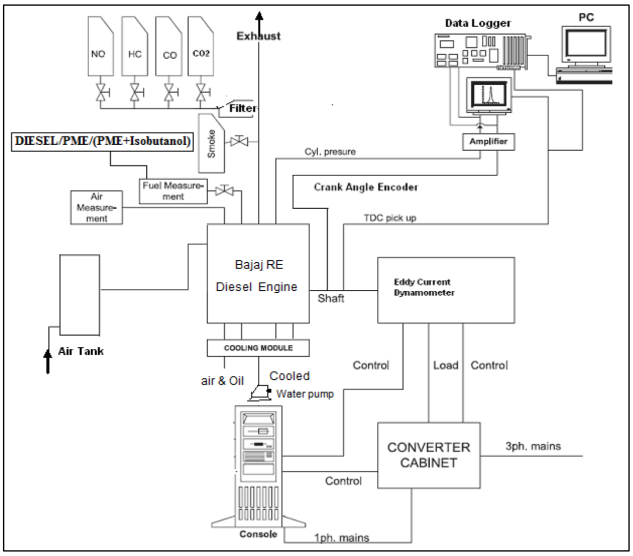

Fig.1. Schematic arrangements of the engine test bed, Instrumentation and data logging system

III. RESULTS AND DISCUSSION

Combustion Pressure variation and Heat Release Rate:

Figures 2 indicate the combustion pressure variation with respect to crank angle at maximum load. In the five fuel samples, 6% isobutanol additive blend in the biodiesel exhibited smooth variation of pressure in both the combustion chambers. Figure 3 and 4 indicate the net and cumulative heat plots of the engine at maximum load. The net heat release rate curves for 6% isobutanol are almost flat with no sudden hikes in the heat release indicating smoother combustion. Quantum combustion can be observed in the main chamber in the net heat release rate curves at successive timings. The cumulative plot for the 6% isobutanol, biodiesel solution is comparatively smoother. Despite the reason that the heat value of isobutanol is lower than that of biodiesel and 6% of the volume is being replaced, the cumulative heat release is more than every solution or neat oils as presented in the Figure 4. The cumulative heat release for the same percentage blend has an edge over the other fuel combinations showing better diffused combustion in the main chamber indicating maximum torque conversion. Approximately, 80 joules /degree is the maximum gain in the cumulative heat at the upper loads with respect to diesel fuel occurs at 70^0 later than TDC position. At the peak cumulative release there is difference of 60 joules/degree referring to the above context. It can be observed uniform shift of 10^0 of crank revolution in the location of peak heat release rate at maximum load and at the immediate lower load. There is a shift of combustion to the main chamber at the maximum load and seemingly not later than 90^0 after the TDC center. The combustion is better than the conventional diesel and this can be acclaimed to the endemic conservation of the heat energy by the additive and containing all the endothermic reactions owing to low temperature combustion prevailed.

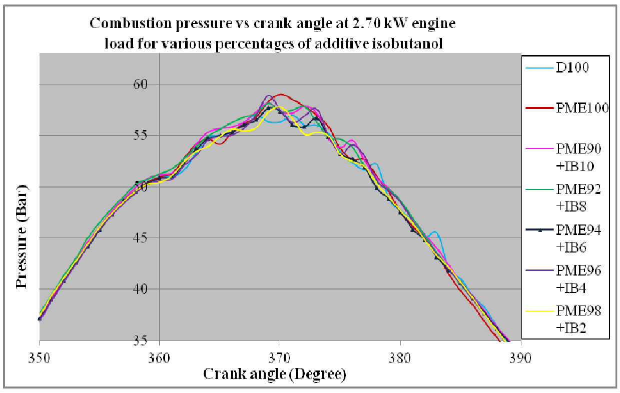

Fig. 2 Combustion pressure plot for various fuel samples at Maximum load on the engine

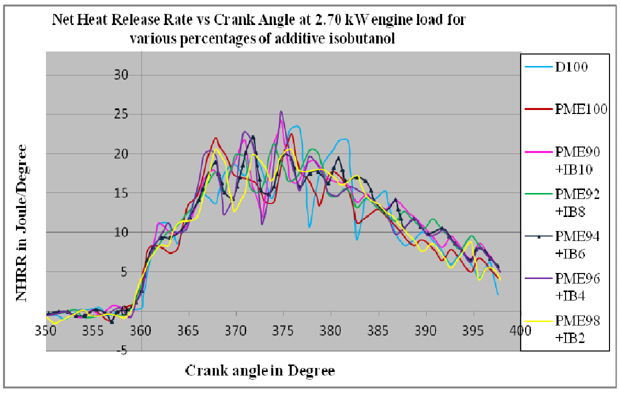

Fig. 3 Computed net Heat release rate for various fuel samples at Maximum load on the engine

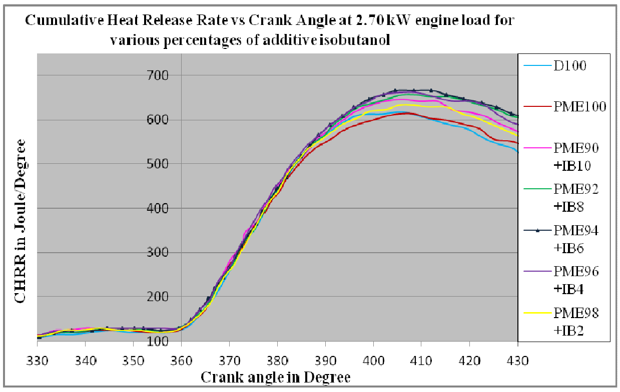

Fig. 4 Computed cumulative Heat release rate for various fuel samples at Maximum load on the engine.

Exhaust gas emissions:

- Exhaust gas temperature:

The variation in exhaust gas temperature for all of the tested fuel samples is shown in Fig.5. In general the exhaust gas temperature for biodiesel is high when compared to conventional diesel fuel. The fuel combinations with isobutanol in biodiesel do not increase exhaust temperatures abnormally with respect to the conventional diesel as is observed in the Fig.5. 6% isobutanol additive in PME reduces Exhaust gas temperature up to 3 ^{0}C at maximum load.

- Engine smoke levels:

The decrease in smoke level in exhaust with respect to the neat diesel fuel operation is appreciable (30% at maximum load operation) as shown in Fig.6. This is an indication of better utilization of oxygen in combustion with 6% additive of isobutanol in biodiesel.

- Hydrocarbon (HC) and Carbon monoxide (CO) emissions:

The HC and CO emission versus brake power at constant speed is shown in Fig.7 & Fig.8. Previous studies on IDI engine indicates lower emissions in exhaust. Additive mixing in biodiesel further reduced the HC and CO emissions. 6% isobutanol additive in biodiesel has reduced HC and CO emissions by71% and 0.02% respectively at maximum load.

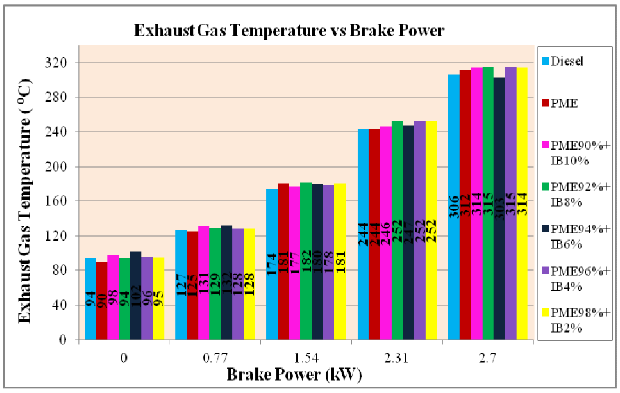

Fig.5. Variation of exhaust gas temperature verses Brake power

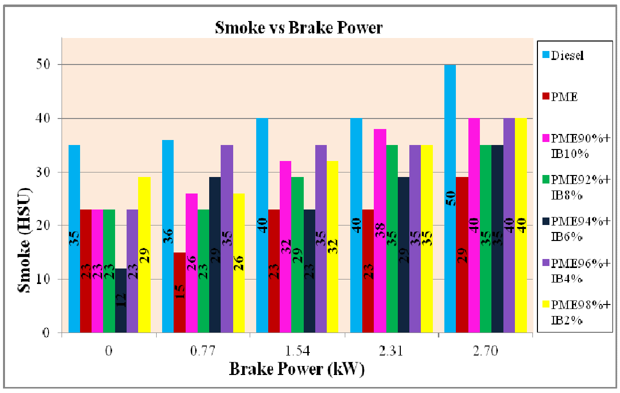

Fig.6. Variation of smoke level verse Brake power

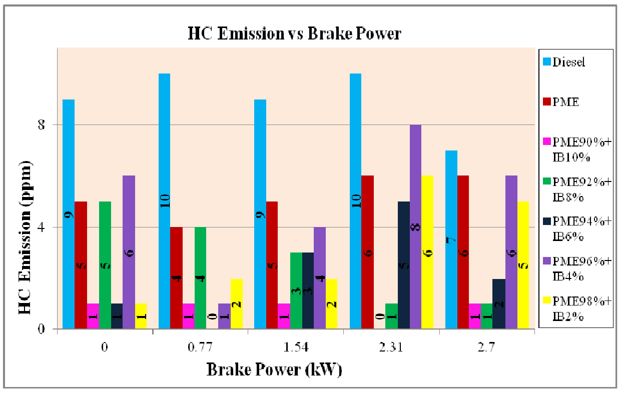

Fig.7. Variation of hydrocarbon emission verses Brake power

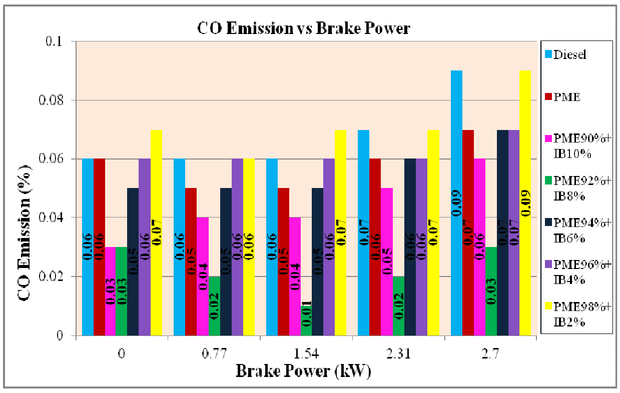

Fig.8. Variation of CO emission verses Brake power

- Carbon Dioxide (CO_2) and Nitrogen Oxide (NO) emissions: CO_2 emission decreased by very lesser quantities as envisaged in Fig.9 because of combustion improvement. Nitrogen Oxide (NO) Emission reduced by 31% at high loads with the 6% isobutanol additive compared with conventional diesel fuel as shown in Fig.10.This may because of colder combustion.

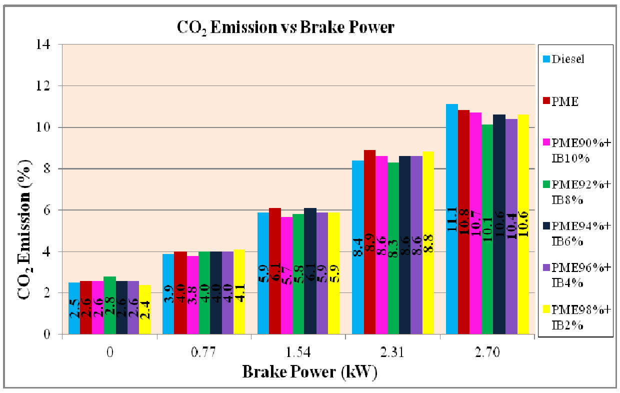

Fig.9 Variation of CO_2 emission verses Brake power

Engine Vibration Analysis:

The cylinder vibration is synonymous with the frequency generated during combustion with a phase difference. It can be observed that 6% isobutanol additive in biodiesel emits lesser amplitudes starting from 5120 Hz to 12800 Hz comparatively. There is an implicit uniformity in the velocity amplitude modulations in the frequency range selected. There is obvious shoot up of amplitude at the high frequency range in the case of diesel fuel. In the mid frequency range from 2560 Hz to 5120 Hz, there is certain attenuation with the additive fuel indicating smoother combustion. The same is portrayed in the time waves to the Fig.11 showing up better combustion in the main chamber with lower traces of exhaust noise through the valve opening.

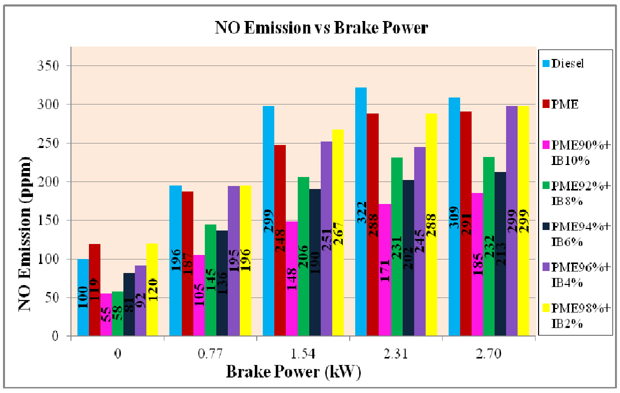

Fig.10. Variation of NO emission verses Brake power

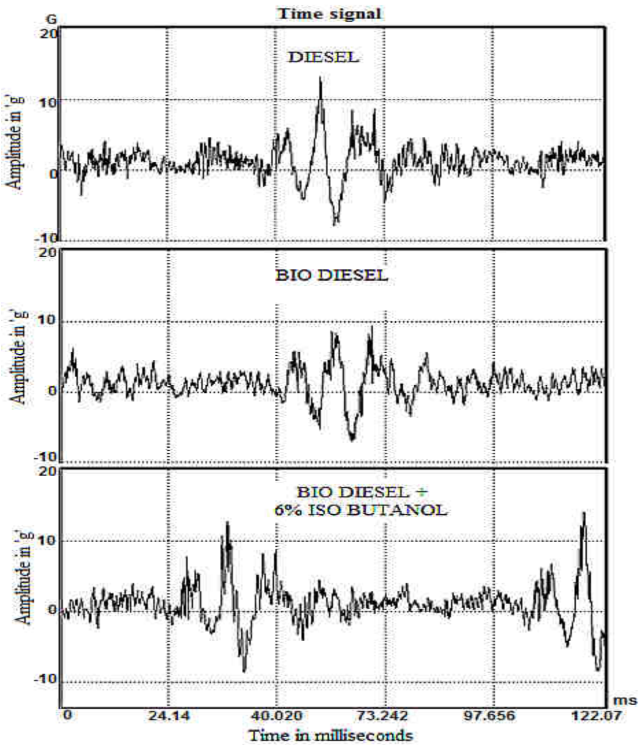

Fig.11 Time wave recorded vertical on the cylinder head at maximum load

IV. CONCLUSION

Small quantities of isobutanol are used as an additive to the Pongamia methyl ester and used in an IDI engine. The combustion, emissions and engine vibration characteristics are evaluated with the suitable isobutanol percentage which gives maximum benefits. It is observed that fuel containing 6% additive in biodiesel performed maximum as replacement to the diesel fuel. The following conclusions may be drawn from the present investigation:

(1) The engine load of 2.70 kW (maximum load) was tried at 1500 rpm for stable operation; it is observed that 6% of additive in biodiesel has given smoother performance in combustion pressure development.

(2) The net heat release rate and cumulative heat release rate quantities were derived from combustion pressure signatures using the first law of thermodynamics and mass fractions burned in the pre-combustion and main combustion chambers envisage better combustion phenomena for 6% of additive. The quantity of heat release is more in the diffused combustion stage indicating better torque conversion and load lifting capacity of the engine with the new fuel.

(3) Exhaust gas temperature and Smoke in HSU are reduced by 3 ^{0}C and 30% respectively in case of 6% isobutanol additive in biodiesel at high load.

(4) Research on IDI engine indicates lower emissions in exhaust. Additive mixing further reduced the HC emission and CO emission to greater extent.

(5) CO2 and NO emission are also reduced at higher loads especially with the additive.

(6) The time waves recorded on the cylinder head envisage better combustion in the main combustion chamber with better combustion sharing in between chambers. The FFT signatures indicate vibration on the cylinder head and foundation and they indicate uniform amplitude modulation revealing smoother combustion for the 6% of additive.

It is concluded that 6% isobutanol additive in PME gives optimum performance indicating suitability to replace diesel fuel.

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