

*Full Length Research Paper*

# Effect of properties of Karanja methyl ester on combustion and NO<sub>x</sub> emissions of a diesel engine

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Accepted 15 April, 2011

The aim of this work is to study the effect of properties of Karanja (*Pongamia pinnata*) methyl ester on combustion, and NO<sub>x</sub> (oxides of nitrogen) emissions of a diesel engine. The properties of the karanja methyl ester such as viscosity, density, bulk modulus, calorific value, iodine value, cetane number, saturation% and oxygen% are considered for this study. Experiments were conducted in a naturally aspirated, single cylinder, four-stroke, stationary, water cooled, constant rpm, in-line (fuel pump-pressure tube-fuel injector) direct injection diesel engine. The engine tests were conducted with karanja methyl ester (with and without preheating), and baseline fossil diesel. The peak pressures and peak heat release rates for methyl ester was slightly higher than diesel fuel. The crank angles for peak pressure of the karanja methyl ester are very close to top dead center. This is probably due to dynamic injection advance caused by their higher bulk modulus. However, the peak cylinder pressures for preheated methyl ester decreases, due to late injection and faster evaporation of the fuel. It was observed that, at full load the oxides of nitrogen emissions of karanja methyl ester are increased by 6%. A significant reduction in oxides of nitrogen emission is observed with preheated methyl ester.

**Key words:** Bulk modulus, combustion, diesel engine, effect, Karanja, methyl ester, NO<sub>x</sub>, properties, preheating, *Pongamia pinnata*.

## INTRODUCTION

During first half of the 20th century, the exhaust gas emissions of internal combustion engines are not recognized as problem, due to lower number of automobiles (diesel engine vehicles). As the number of automobiles grew along with world population; the air pollution became an ever increasing problem. This put a major restriction on the engine design during the 1980s and 1990s. Due to technological advancements, emissions have been reduced by over 90% since the 1940s; they are still a major problem for the environment due to exponential increase of automobile population (Pulkrabek, 2003).

One of the major emissions produced by diesel engines is oxides of nitrogen (NO<sub>x</sub>). In diesel engines, the combustion process forms oxides of nitrogen (NO<sub>x</sub>) in which the nitric oxide (NO) is abundant; a small portion of the NO oxidizes into nitrogen dioxide (NO<sub>2</sub>) at low temperatures in the presence of oxygen. The sum of NO and NO<sub>2</sub> is called NO<sub>x</sub>. The formation of NO<sub>x</sub> is dependent on the temperatures during the combustion, the amount of oxygen (O<sub>2</sub>) and nitrogen (N<sub>2</sub>) present in the charge and

the time available for them to react with each other.

NO<sub>x</sub> are the precursor pollutants which can combine to form photochemical smog. These irritate the eyes and throat, reduces the ability of blood to carry oxygen to the brain and can cause headaches, and pass deep into the lungs causing respiratory problems for the human beings. Long-term exposure has been linked with leukemia. Therefore, the major challenge for the existing and future diesel engines is meeting the very tough emission targets at affordable cost, while improving fuel economy. The focus on NO<sub>x</sub>, reductions to meet stringent emission norm 'EURO- V' may represent a major hurdle.

Different methods are being used to reduce NO<sub>x</sub> emissions from the diesel engines. One is improving the engine technology and the other is using of alternate or oxygenated fuels to increase combustion efficiency. Over the past several years, there has been increased interest in alternate fuels to control exhaust emissions. Therefore, from the point of view of protecting our surrounding environment, and human health, it is necessary to develop alternate fuels with properties comparable to fossil diesel.



Figure 1. Karanja flowers.



Figure 2. Karanja pods.

Vegetable oil is one such source. India has about 86 types of oilseed-bearing perennial trees (Mitra, 1963) of which Karanja seed (*P. pinnata*); mahua (*Madhuca indica*), neem (*Azadirachta*) and Jatropha (*Jatropha curcas*) are the important ones. Vegetable oils have comparable properties with diesel fuel. However, using straight vegetable oil lead to the clogging of the fuel injectors and there is a problem of starting, especially when the engine is cold. To avoid these problems, the straight vegetable oils can be chemically treated to enhance its properties, after which the vegetable oil is known as methyl ester (ME) or biodiesel. The ME is often referred to as fatty acid methyl ester (FAME).



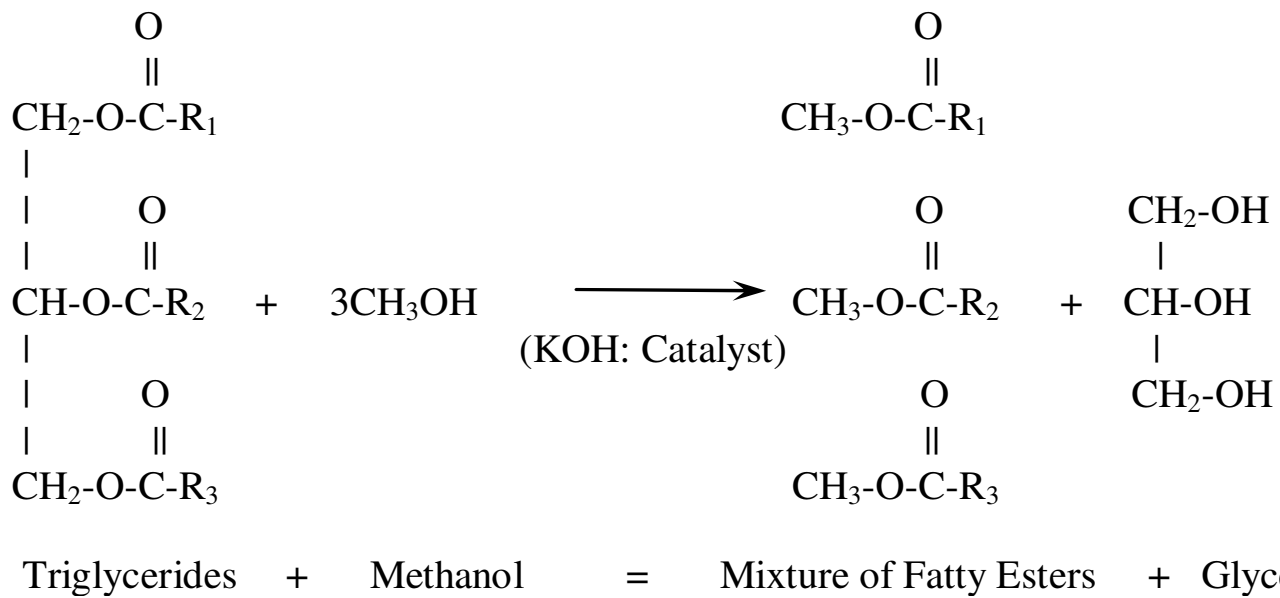
Figure 3. Karanja seeds.



Figure 4. Karanja oil.

### Karanja (*Pongamia pinnata*) oil

*Pongamia*, a medium sized glabrous tree grown in many parts of India and Australia (Vivek and Gupta, 2003). *Pongamia* is popularly known as Karanja in India. Karanja belongs to the family Leguminaceae (Meher et al., 2004) and its botanical name is *P. Pinnata*. Karanja tree bears flowers (Figure 1), and then pods, which after 10 to 11 months gets matured and changes to a tan color (Figure 2) in the month of May to June. The pods are flat to elliptic in shape and contain one (or two) kidney shaped brownish red seeds (or kernels) as shown in Figure 3. The oil content of karanja seed is about 33% (Kumar and Sharma, 2008). The fresh extracted oil is yellowish orange to brown and rapidly darkens on storage as shown in Figure 4.



**Figure 5.** Mechanism of the base (KOH)-catalyzed transesterification process.

**Table 1.** ASTM methods and instruments used to measure physico-chemical properties of fuels.

Fuel property	Method	Instrument	Model
Density	D 1298	Hydrometer	Petroleum instruments, India
Flash and fire points	D 92	Cleveland open-cup	Petroleum instruments, India
Calorific value	D 240	Bomb CALORIMETER	Parr, UK
Kinematic viscosity	D 445	Kinematic Viscometer	Setavis, UK

### Preparation of karanja oil methyl ester

Karanja oil contains up to 20% (wt.) free fatty acids (Naik et al., 2008; Kalbande, 2008; Bryan, 2009; Sanaz et al., 2010). The methyl ester is produced by chemically reacting the karanja oil with an alcohol (methyl), in the presence of a catalyst (KOH). A two-stage process is used for the esterification (Gerpen, 2003; Aleks, 2000; Tapasvi et al., 2005; Jindal et al., 2010) of the karanja oil. The first stage (acid-catalyzed) of the process is to reduce the free fatty acids (FFA) content in karanja oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid-98% pure) in one hour time of reaction at 55°C. In the second stage (alkali-catalyzed), the triglyceride portion of the karanja oil reacts with methanol and base catalyst (sodium hydroxide-99% pure), in one hour time of reaction at 65°C, to form methyl ester and glycerol as shown in Figure 5.

To remove un-reacted methoxide present in raw methyl ester, it is purified by the process of water washing with air-bubbling. The methyl ester (or biodiesel) produced from pongamia oil is known as karanja oil methyl ester (KOME) or karanja biodiesel.

### CHARACTERIZATION OF METHYL ESTER

The measurement of physico-chemical properties of the fuels were carried out according to ASTM D6751-02 (Standard Specification for Biodiesel Fuel (B100) Blend Stock for Distillate Fuels standards (ASTM, 2002)). The specifications and manufacturers of the instruments used were given in Table 1. The physico-chemical properties of karanja methyl ester are different from fossil diesel. The physical properties of biodiesel will be influenced on combustion, flow, and storage behaviors (Jo-Han et al., 2010). The independent effects of the biodiesel properties on various operational aspects of diesel engine when compared with fossil diesel are discussed.

#### Fatty acid composition and carbon chain

The building blocks of fatty esters, the fatty acid chain and the alcohol moiety, influence fuel properties and varying either can lead to a change in fuel properties (Knothe, 2010). As shown in Figure 6, the feed stock dependent fatty acid compositions (hydrocarbon chains)

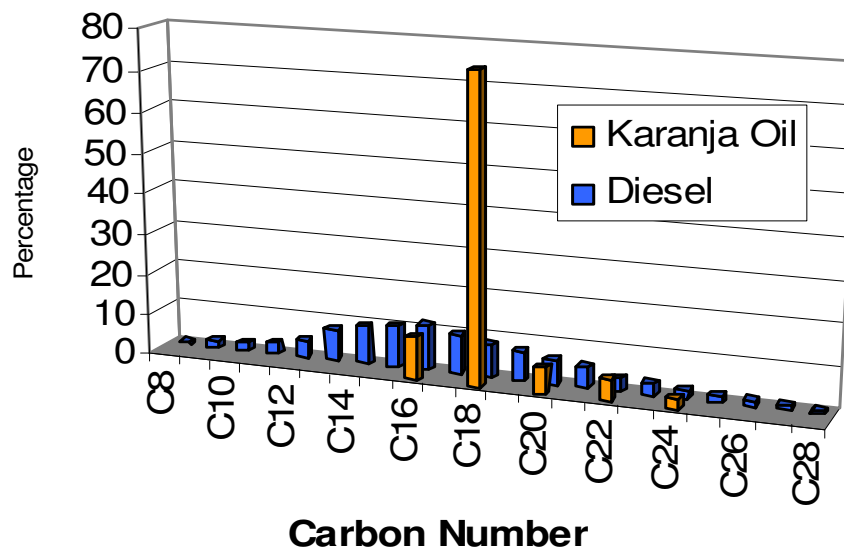


Figure 6. Carbon number distribution.

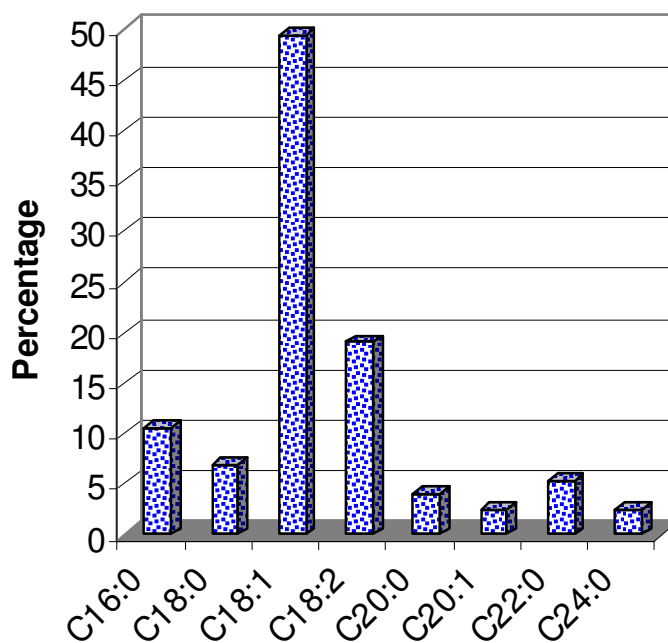


Figure 7. Fatty acids in karanja oil.

of karanja oil vary from  $C_{16}$  to  $C_{24}$ , with the long chain oleic acid ( $C_{18:1}$ ), linoleic acid ( $C_{18:2}$ ), palmitic acid ( $C_{16:0}$ ), stearic acid ( $C_{18:0}$ ), and behenic acid ( $C_{22:0}$ ) are the highest (Kumar and Sharma, 2008; Bala et al., 2011). The amount of fatty acids present in karanja oil is oleic acid: 49.4%, linoleic acid: 19%, palmitic acid: 10.6%, stearic acid: 6.8%, behenic acid: 5.3%, as shown in Figure 7. This oil contains 29% saturated fatty acids (SFA), 52% of mono-unsaturated fatty acids (MUFA) and

19% of poly-unsaturated fatty acids (PUFA), as shown in Figure 8.

The carbon chain of diesel fuel includes both medium ( $C_8$ - $C_{12}$ ) and long ( $C_{14}$ - $C_{32}$ ) carbon chain. The hydrocarbons in diesel fuel range in size from 8 carbon atoms per molecule ( $C_8$ ) to 32 carbon atoms per molecule ( $C_{32}$ ) (Applewhite, 1980). The peak in the carbon-number distribution occurs at about 13 to 19 carbon atoms per molecule ( $C_{13}$ - $C_{19}$ ), as shown in Figure 6.

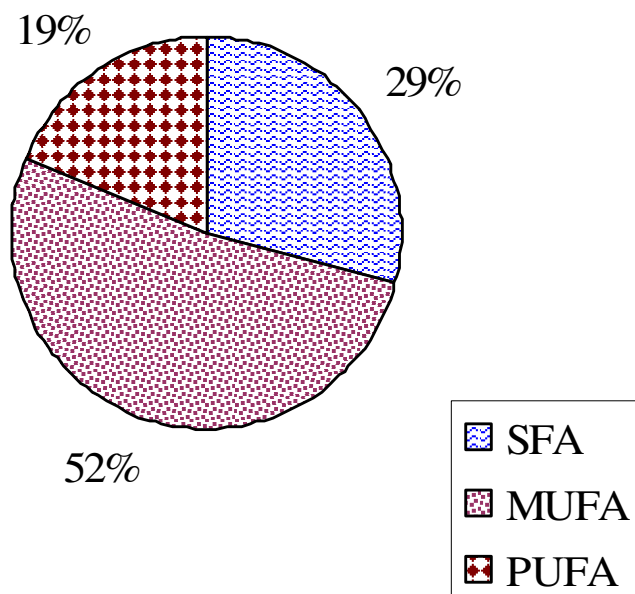


Figure 8. Saturated and unsaturated fatty acids in karanja oil.

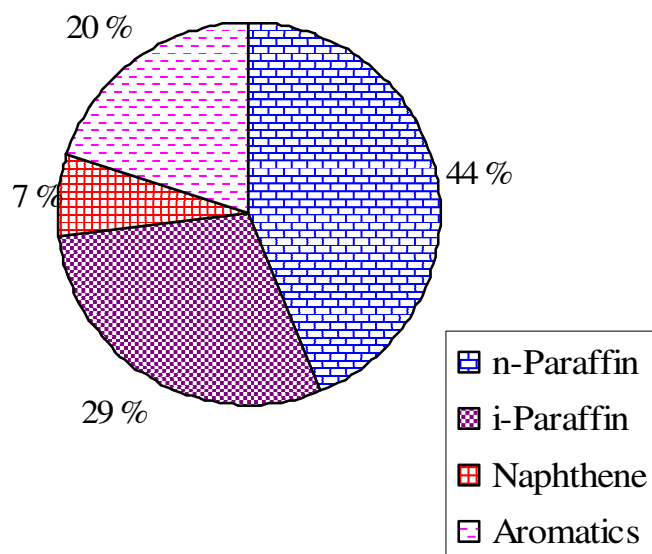


Figure 9. Composition of fossil diesel.

The fossil diesel fuel typically contains over 400 distinct types of organic compounds. Approximately 80% (vol.) of the diesel fuel contains alkanes, with the remainder (that is, 20%) comprised of aromatic molecules. Typical fossil diesel contains approximately 44% of n-Paraffin, 29% of i-Paraffin and 7% of Naphthene as shown in Figure 9. The aromatics containing multiple benzene rings are known as poly-aromatic hydrocarbons (PAHs). These aromatics include polycyclic aromatic compounds containing 2, 3, 4, and 5 fused benzene rings. Benzene

rings will act as nuclei for growth of undesired soot (Akihama et al., 2002).

### Iodine value

The iodine value (IV) shows the level of un-saturation of the fuel, which means higher the percentage of unsaturation, larger will be the iodine value (Heinrich et al., 1999). Iodine value of the oil remains little affected by transesterification (Jindal et al., 2010). This is because of the fact that the process is not affecting the degree of unsaturation of the oil. The KOMÉ with 70.8% unsaturation (29.2% saturates) has an iodine value of 81 and this value is well within the permissible limits (<120), as shown in Table 2.

### Cetane number

The ignition quality of the fuel is measured by cetane number (CN) and it measures how easily ignition occurs. A fuel with a good ignition quality has a higher cetane number, where the ignition delay period between the start of fuel injection and the onset of auto ignition is short (Johan et al., 2010). The higher the CN, the shorter the ignition delay time and vice versa. The CN assists in smooth combustion with lower knocking characteristics in diesel engines. The CN requirement for the engine depends on the design, size, speed, and load. The CN depends on fuel composition and influences the beginning of the process of combustion and emissions. The CN of methyl ester depends on fatty acids of feedstock (Tapasvi et al., 2005). The CN for KOMÉ is 55.84 (Kumar and Sharma, 2008) and for fossil diesel is 48.

### Oxygen and calorific value

In general, the calorific value (or heat of combustion) of methyl ester is less than that of fossil diesel due to presence of C-O and C-C bonds (Romulo et al., 2011). The fossil diesel is made up of a mixture of various hydrocarbon molecules and contains little oxygen (up to 0.3%) and small amount of sulfur (0.25%), while the methyl ester consists of three basic elements namely: carbon, hydrogen, significant amount of oxygen and negligible amount of sulfur, as shown in Table 2. The increase of O<sub>2</sub> in methyl ester (biodiesel) is related to the reduction of C and H<sub>2</sub>, causes the lower value of lower calorific value (LCV) of KOMÉ as compared to that of fossil diesel, because O<sub>2</sub> is ballast in fuel and 'C and H<sub>2</sub>' are the sources of thermal energy (Gerpen et al., 2004). Therefore, the stoichiometric air-fuel ratio of KOMÉ will be lower than fossil diesel. The KOMÉ contains 11% of O<sub>2</sub>; as a result the combustion efficiency of the KOMÉ will be increased (Lebedevas and Vaicekaskas, 2004).

**Table 2.** Physico-chemical properties of test fuels in comparison to ASTM biodiesel standards.

Property	Units	Diesel (HC)	KOME (FAME)	ASTM D 6751-02
Carbon Chain	Cn	C8-C28	C16-C24	C12-C22
Density ( $\rho$ )	gm/cc	0.825	0.875	0.87-0.89
Bulk Modulus ( $\beta$ ) @ 20 MPa (Boehman and Alam, 2003)	MPa	1475	1800	N A
Kinematic Viscosity (KV) @ 40 °C	cSt	2.25	4.2	1.9-6.0
Cetane Number	----	48	55.84	48-70
Iodine Value	g Iodine/100 g	38	81	120 max.
Oxygen	%	0.3	11	11
Air/Fuel ratio (Stoichiometric)	-----	14.86	13.8	13.8
Lower Calorific Value	kJ/kg	42 500	38 300	37 518
Sulfur	%	0.25	0	0.05
Flash Point (open cup)	°C	66	174	130 min.
Molecular weight	-----	226	281	292
Color	-----	Light yellow	Yellowish orange	----

### Density and bulk modulus

The values of density ( $\rho$ ) and bulk modulus ( $\beta$ ) of the methyl ester are more than that of fossil diesel as shown in Table 2. This high density compensates the lower value of the heat of combustion of the methyl ester. The bulk modulus ( $\beta$ ) of a liquid fuel is defined as the pressure required to produce unit volumetric strain and is given by the Equation (1) (Boehman and Alam, 2003; Obert, 1973). The ' $\beta$ ' is a function of fuel temperature (T), pressure (p), and density. The velocity (s) of propagation of the pressure waves (or pulses) through the fuel discharge pipe is given by the Equation (2) (Giffen and Rowe, 1939; Bakar and Firoz, 2005; Brown, 1966; Rao PV, 1993). The term 'c' is the velocity of sound and 'g' is acceleration due to gravity:

$$\beta = \rho \cdot (\partial p / (\partial \rho))_T \text{ ----- Equation (1)}$$

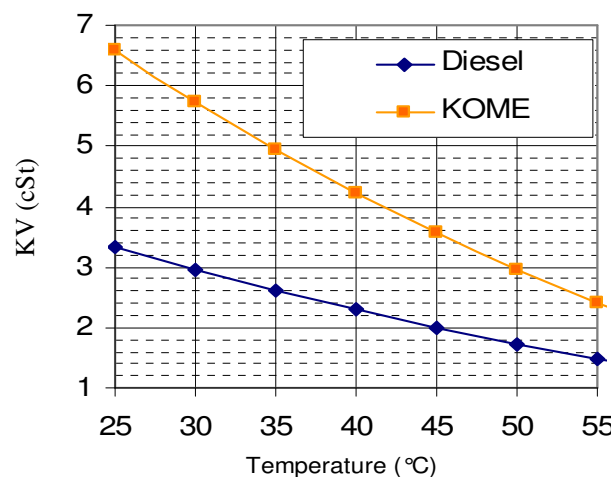
$$s = c \cdot \sqrt{(\beta \cdot g / \rho)} \text{ ----- Equation (2)}$$

### Flash point

The flash point temperature of KOME is higher than that of fossil diesel, because the karanja methyl ester does not have the light fractions. Fuel with high flash point is highly coveted, as the risk associated with fuel transportation is greatly minimized, therefore the safety of KOME is ensured.

### Kinematic viscosity

The kinematic viscosity (KV) influences the injection characteristics (spray pattern and depth of penetration) of

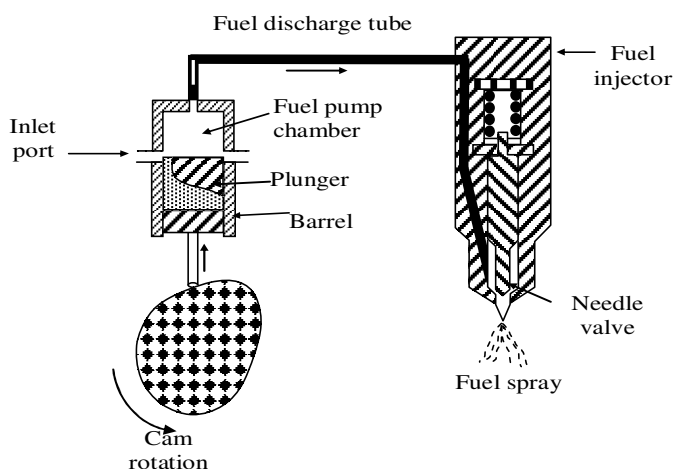
**Figure 10.** Kinematic viscosity versus temperature.

the fuel, and the quality of filtering. Viscosity of the liquid fuels decreases with the increase of temperature, which in turn decreases the emissions of non-combusted products. The viscosity of fossil diesel and KOME at 30 °C is 3.0 and 5.8 cSt respectively, as shown in Figure 10. This high viscosity of methyl ester reduces the leakage in plunger and barrel pair of the fuel pump (Gerpen et al., 2004) and minimum viscosity limits are imposed to prevent the fuel from causing wear in the fuel injection pump. The viscosity of KOME at 50 °C is 3.0 cSt and is equal to that of diesel fuel at engine room temperature of 30 °C., as shown in Figure 10.

From the testing of physico-chemical properties of KOME (or Karanja biodiesel), it is observed that, these properties are meeting the specifications of ASTM biodiesel standards as shown in Table 2 and KOME was

**Table 3.** Test engine specifications.

Engine make and model	Kirloskar (India), AV1
Maximum power output	3.72 kW
Method of cooling	Water cooled
Bore x Stroke	80 mm x 110 mm
Compression ratio	16.5
Rated speed (constant)	1500
Fuel injection system	In-Line, Direct Injection
Nozzle opening pressure	205 bar
BMEP @1500 rpm	5.31 bar

**Figure 11.** Traditional cam-driven, in-line fuel injection system.**Figure 12.** Exhaust gas analyzer.**Table 4.** Specifications of exhaust gas analyzer.

Measuring range	Precision	Resolution
0-2000 ppm	+/- 5 ppm	1 ppm

found suitable for diesel engine application.

## EXPERIMENTATION, INSTRUMENTATION AND PROCEDURE

Experiments were performed on a naturally aspirated, 4-stroke cycle, single cylinder, direct injection diesel engine, with the specifications shown in Table 3.

This engine employs the traditional, cam-driven, in-line fuel injection system as shown in Figure 11. It consists of a fuel pump (jerk pump), a medium pressure tube (or fuel discharge tube) of length 585 mm (23 inch. approx.), and an injector (or atomizer). The pressure pulses (or waves) are generated by the fuel pump plunger and the 'column of fuel' is formed by the pump chamber, discharge tube, and the injector. This 'column of fuel' behaves like a stiff spring. The pressure pulses propagate through the 'column of fuel' to develop pressure at the nozzle end. When the fuel pressure reaches a pressure more than that required to open the needle valve of the injector, the needle valve is lifted to inject the fuel into the cylinder. For fuels with higher bulk modulus of compressibility, a more rapid transfer of the pressure wave takes place from pump end to the injector needle valve and the earlier needle lift causes an advanced (or early) injection. Therefore, the fuel like biodiesel (KOME), which is less compressible will inject prematurely.

This engine is tested with baseline diesel, and KOME. Diesel engine is also tested with preheated KOME (KOME\_H) to find the

influence of reduced viscosity on combustion, and NO<sub>x</sub> emission characteristics. For preheating KOME; heating devices were placed along the fuel discharge tube shown in Figure 11. The fuel injection was performed at a static injection timing (optimum) of 23° BTDC set for diesel fuel. The engine is allowed to warm up at constant speed of 1500 rpm, until the cooling water temperature reaches a steady state of 80°C. Eddy current dynamometer is used to measure the power (or torque). Engine brake load was varied in five equal steps (at 0, 0.93, 1.86, 2.79 and 3.72 kW), ranging from 0 to 100% of the rated power output of 3.72 kW. A computer interfaced piezoelectric sensor (water cooled) of range 0 to 145 bar was used to record the in-cylinder pressure. Apex innovations, Pune, India, software: C7112 is used to record the in-cylinder combustion pressure. Pressure signals were obtained using data acquisition system. The average pressure data from 20 consecutive cycles were used for calculating combustion pressure parameters. The net HRR and cumulative heat release (CHR) were calculated from the acquired data.

The NO<sub>x</sub> emissions of the engine were measured with the exhaust gas analyzer (make: MRU, Germany and model: Delta 1600 L) shown in Figure 12. Table 4 shows the technical specifications of the exhaust gas analyzer used for NO<sub>x</sub> measurement.

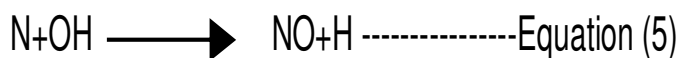
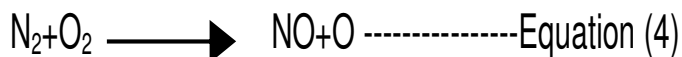
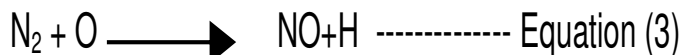


Figure 13. Reactions of Zeldovich mechanism.

### Combustion and NOx formation

The combustion process in diesel engines is mainly divided into three phases. The first phase of combustion is called as ignition delay (ID), in which the tiny fuel droplets evaporates and mixes with high temperature (or high pressure) air. The delay period depends mainly on fuel cetane number (CN), and temperature of the air. The ID is also influenced by the fuel temperature. The second phase of combustion is called as period of rapid combustion or premixed combustion. In this phase the air-fuel mixture undergoes rapid combustion, therefore the pressure rise is rapid and releases maximum heat flux. In diesel engines, thermal NOx is mainly produced during premixed combustion. The third phase of combustion is called as period of controlled combustion. In this period, the fuel droplets injected during the second stage burn faster with reduced ID due to high temperature and pressure. In this third phase the pressure rise is controlled by the injection rate and the combustion is diffusive mode.

A number of fuel properties have been shown to effect the emissions of NOx (Robert et al., 2001). Fuel properties, such as density, viscosity, sound velocity, bulk modulus, cetane number, oxygen content, and so on, have significant effects on the start of injection, start of combustion, and premixed and diffusion burn peak, and over these on the emissions including NOx (Breda, 2006).

Thermal NOx refers to oxides of nitrogen formed through high temperature oxidation of nitrogen found in air during premixed combustion. The rate of thermal NOx is primarily a function of temperature and the residence time of nitrogen at that temperature. Usually at a temperatures of above 2100K, the nitrogen and oxygen disassociate and participate in a series of three principal reactions (Equations 3, 4 and 5) and this mechanism is known as Zeldovich mechanism (Heywood, 1988) shown in Figure 13.

## RESULTS AND DISCUSSION

### Combustion analysis

The combustion characteristics are heavily influenced by the properties of the fuel such as cetane number, calorific value, oxygen content and bulk modulus. A marked difference in the combustion characteristics are expected due to the distinct variations in fuel properties between KOME and fossil diesel. The KOME is expected to combust earlier from the shorter ignition delay caused by higher cetane number. The combustion analysis is explained in terms of peak pressure; net heat release rates (Net HRR), cumulative heat release (CHR) and exhaust gas temperatures (EGT) as follows:

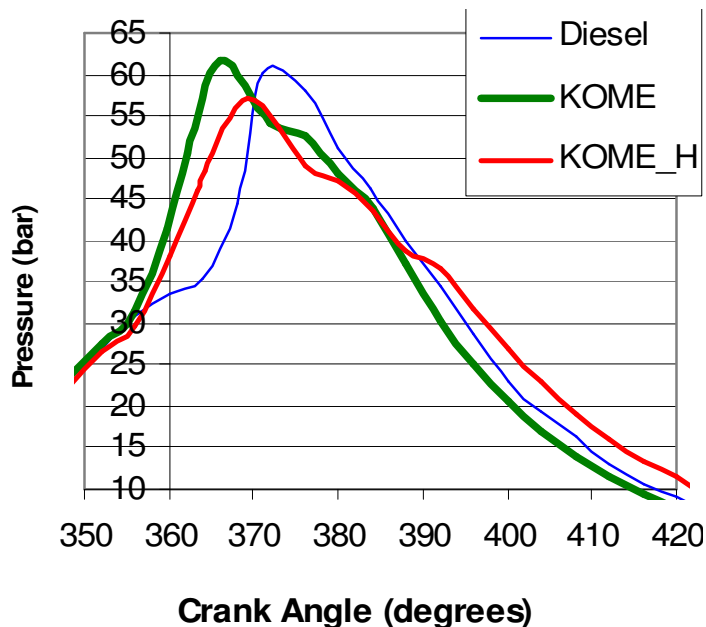


Figure 14. Cylinder pressure.

**Peak pressures:** Figure 14 shows the variation of cylinder pressure with respect to crank angle at maximum output of 3.72 kW. It is observed that, the KOME is burning close to TDC and the peak pressure is slightly higher than that of diesel fuel; even though the KOME is having lower value of LCV. The KOME advances the peak pressure position as compared to fossil diesel because of its higher bulk modulus and cetane number. This shift is mainly due to advancement of injection due to higher density and earlier combustion due to shorter ignition delay caused by higher cetane number of KOME. When, a high density (or high bulk modulus) fuel is injected, the pressure wave travels faster from pump end to nozzle end, through a high pressure in-line tube (Yamane et al., 2001). This causes early lift of needle in the nozzle, causing advanced injection. Hence, the combustion takes place very close to TDC and the peak pressure slightly high due to existence of smaller cylinder volume near TDC, as shown in Figure 15.

However, the peak pressures of preheated methyl ester (that is, KOME\_H) are less than that of fossil diesel and KOME. When the engine is running on KOME\_H, the fuel injection is slightly delayed, due to decrease in bulk modulus of KOME with the increase in fuel (methyl ester) temperature. The reasons for lower peak pressures of preheated KOME is also attributed to earlier combustion caused by short ignition delay (due to faster evaporation of KOME\_H) at its preheated temperature of 50°C.

**Net heat release rates (net HRR) and cumulative heat release (CHR):** Figures 16 and 17, shows the net heat release rate (HRR) and cumulative heat release (CHR). A noticeable change in combustion phases were observed



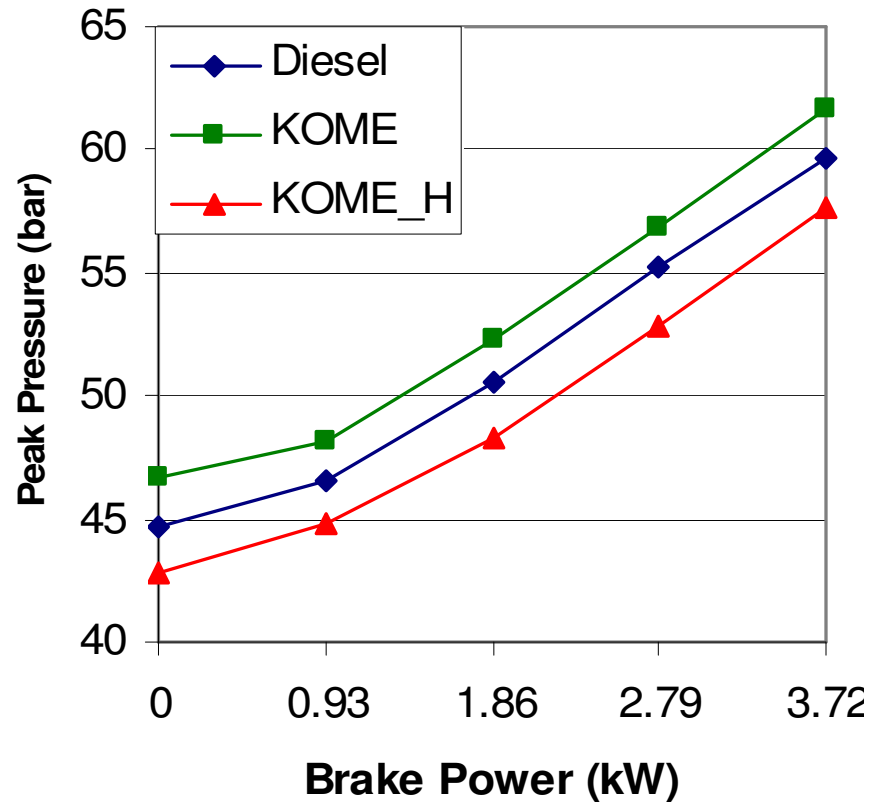


Figure 15. Peak pressure.

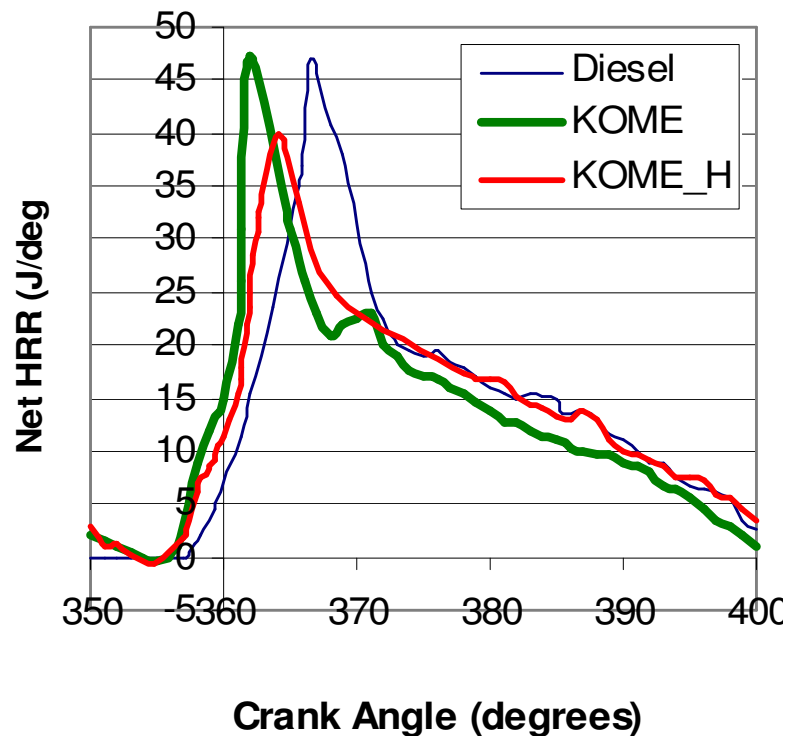


Figure 16. Net HRR at maximum output.

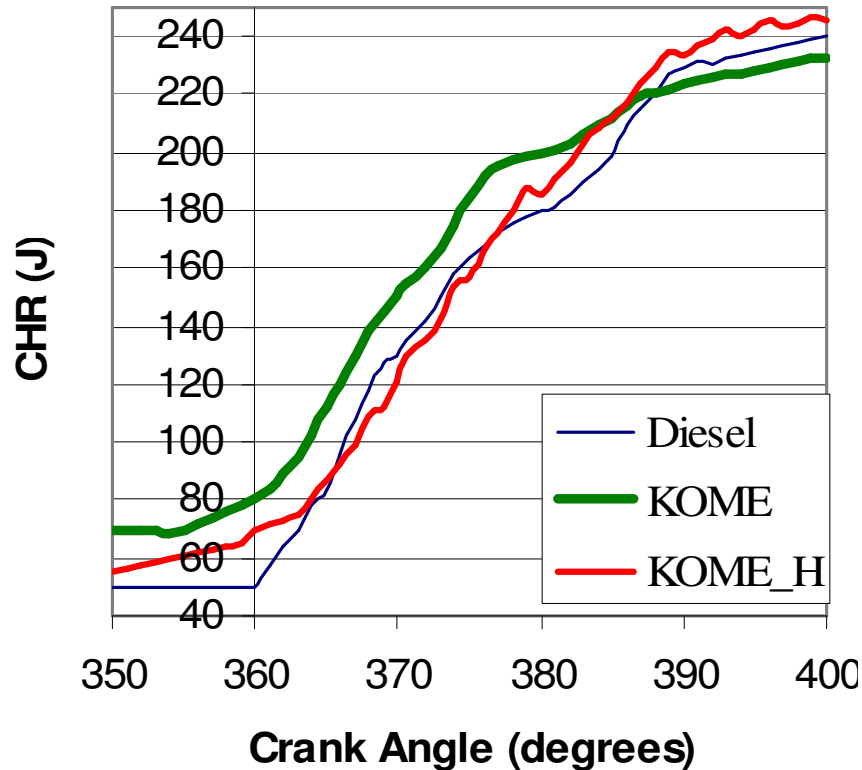


Figure 17. CHR at maximum output.

between KOME and KOME\_H. The peak value of premixed combustion was more for KOME, than that of KOME\_H, and the diffusive combustion phase was more for KOME\_H, than that of KOME. As the fuel temperature increases, the ignition delay decreases and the main combustion phase, that is, diffusion controlled combustion increases. At the time of ignition, less quantity of air-fuel mixture is prepared for combustion. This is due to faster evaporation of the preheated methyl ester. Therefore, more burning occurs in the diffusion phase rather than in the premixed phase.

The cumulative heat release is more for KOME\_H than that of KOME and this indicates that there is a significant increase of combustion in diffusion mode. This increase in heat release is mainly due to better mixing and evaporation of KOME\_H, which leads to complete burning. The heat released by the KOME is less due to poor mixing of KOME with the surrounding air because of its high viscosity.

**Exhaust gas temperatures:** Temperature of exhaust gases, leaving the engine cylinder represents the extent of temperature reached in the cylinder during combustion. It is observed that, with increasing load the cylinder pressure increases and more of the fuel is burnt leading to an increase in temperatures as shown in Figure 18. The temperature of exhaust gases is observed to be

higher with fossil diesel as compared to KOME for entire range of power output. This is expected as the calorific value (or heat of combustion) of fossil diesel is more than that of KOME; therefore greater amount of heat is released in the combustion chamber leading to higher temperature. Also, there is an advanced combustion of KOME (Figure 16) due to its higher bulk modulus and cetane number, when compared to fossil diesel. Therefore, the heat released by fossil diesel combustion is late by few degrees and thus more heat gets exhausted. The exhaust gas temperatures of preheated KOME (KOME\_H) are higher than that of KOME, which indicates the increase of diffused combustion due to high rate of evaporation and improved mixing between methyl ester and air. Therefore, as the fuel temperature increases, the ignition delay decreases and the main combustion phase (that is, diffusion controlled combustion) increases, which in turn raises the temperature of exhaust gases.

#### NO<sub>x</sub> analysis

Results show that for all the fuels the increased engine load promoting NO<sub>x</sub> emission as shown in Figure 19. Since the formation of NO<sub>x</sub> is very sensitive to temperature, therefore higher loads promote cylinder charge temperature, which is responsible for thermal (or

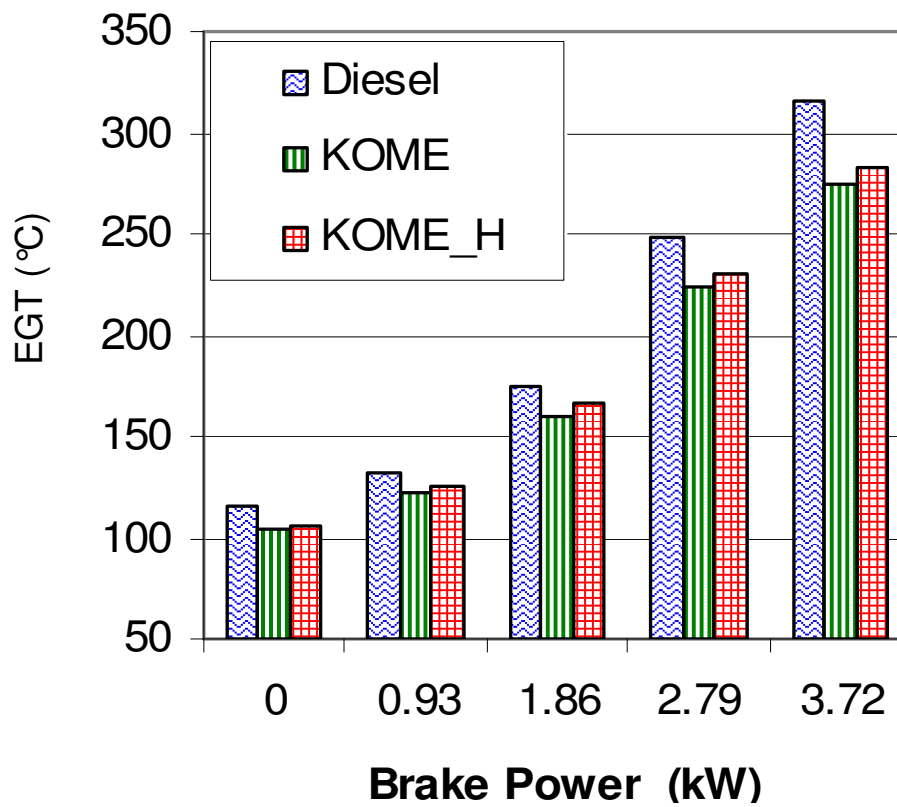


Figure 18. Exhaust gas temperatures.

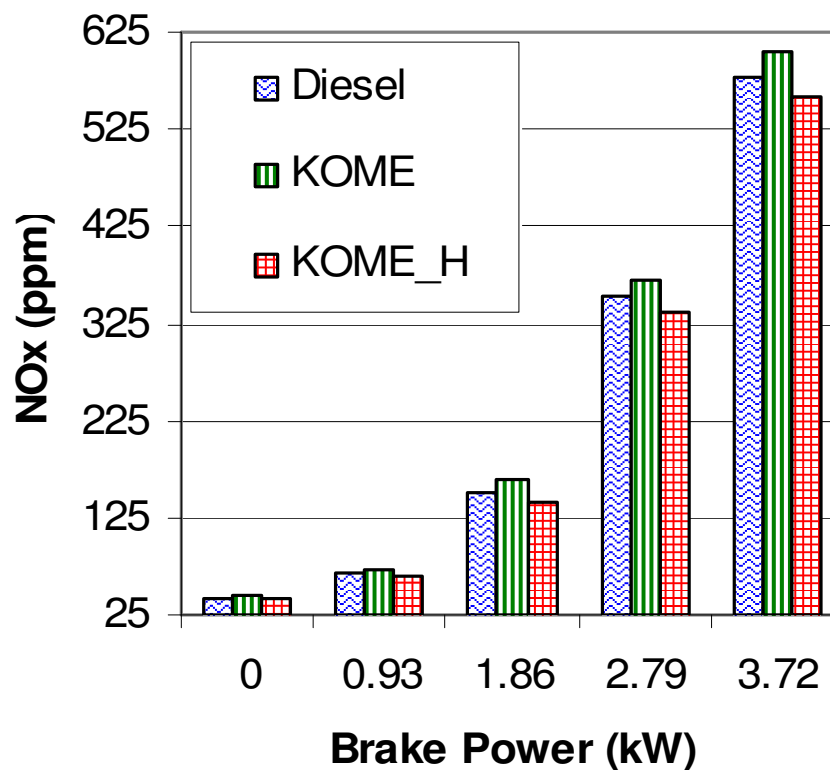


Figure 19. Oxides of nitrogen.

Zeldovich) NO<sub>x</sub> formation.

The KOMÉ having long carbon chain (C<sub>16</sub>-C<sub>24</sub>) is producing more NO<sub>x</sub> than that of fossil diesel having both medium (C<sub>8</sub>-C<sub>14</sub>) as well as long chain (C<sub>16</sub>-C<sub>28</sub>) as shown in Figures 6 and 19. The increase in NO<sub>x</sub> emission might be an inherent characteristic of KOMÉ due to the presence of 51.8% of mono-unsaturated fatty acids (MUFA) and 19% of poly-unsaturated fatty acids (PUFA) as shown in Figure 8. That means, the long chain unsaturated fatty acids (MUFA and FUPA) such as oleic C<sub>18:1</sub> and linoleic C<sub>18:2</sub> (Figure 7) fatty acids are mainly responsible for higher levels of NO<sub>x</sub> emission (Myo, 2008). Another reason for higher NO<sub>x</sub> levels is the oxygen (11%) present in the methyl ester. The presence of oxygen in KOMÉ leads to improvement in oxidation of the nitrogen available during combustion. This will raise the combustion bulk temperature responsible for thermal NO<sub>x</sub> formation (Figure 13).

The production of more NO<sub>x</sub> with KOMÉ fueling is also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the in-line fuel injection system. KOMÉ is less compressible due to the higher bulk modulus, causing nozzle opening pressure to be exceeded prematurely. This earlier injection leading to advancement in combustion timing where a stronger premixed combustion phase (Figure 16) follows (Jo-Han et al., 2010). This in turn increases the peak in-cylinder temperature, which increases the rate of NO<sub>x</sub> formation.

The fuel spray properties may be altered due to differences in viscosity and surface tension. The spray properties affected may include droplet size, droplet momentum, degree of mixing, penetration, and evaporation. The change in any of these properties may lead to different relative duration of premixed and diffusive combustion regimes. Since the two burning processes (premixed and diffused) have different emission formation characteristics, the change in spray properties due to preheating of the KOMÉ are lead to reduction in NO<sub>x</sub> formation. As fuel temperature increases, there is an improvement in the ignition quality, which will cause shortening of ignition delay. A short ignition delay period lowers the peak combustion temperature which suppresses NO<sub>x</sub> formation (Hess et al., 2005). Lower levels of NO<sub>x</sub> is also attributed to retarded injection, improved evaporation, and well mixing of KOMÉ\_H due to its low viscosity at preheated temperature of 50°C.

## Conclusions

The present work confirms the influence of the higher bulk modulus of methyl ester (biodiesel) on injection and combustion timings of a diesel engine operated by in-line fuel injection system. The higher levels of NO<sub>x</sub> emission is attributed to the combined effect of bulk modulus, cetane number, oxygen, and unsaturated fatty acids. Decrease in premixed combustion and increase in

diffused combustion is observed with preheated methyl ester. The reduction in peak value of premixed combustion is leads to the reduction of NO<sub>x</sub> levels.

## REFERENCES

- Akihama K, Takatori Y, Nakakita K (2002). Effect of Hydrocarbon Molecular Structure on Diesel Exhaust Emissions. Research Report, R and D Rev. Toyota CRDL, 37(3): 46-52.
- Aleks K (2000). The Two-Stage adaptation of Mike Pelly's Biodiesel Recipe, Available online: [http://journeytoforever.org/biodiesel\\_aleks.html](http://journeytoforever.org/biodiesel_aleks.html).
- Anonymous (2002c). American Society for Testing and Materials(2002), Standard Specification for Biodiesel Fuel (B100).
- Applewhite TH (1980). Kirk-Othmer Encyclopedia of Chemical Technology, 3<sup>rd</sup> Edition, John Wiley and Sons, Inc., New York, 9: 795-811.
- ASTM (2002). Blend Stock for Distillate Fuels, Designation D6751-02, International, West Conshohocken, PA., pp: 1-6.
- Bakar RA, Firoz T (2005). Numerical analysis of pressure pulses in the jerk fuel injection systems. Am. J. Appl. Sci., 2(5): 1003-1007.
- Bala M, Nag TN, Kumar S, Vyas M, Kumar A, Bhogal NS (2011). Proximate Composition and Fatty Acid Profile of *Pongamia pinnata*, a Potential Biodiesel Crop. J. Am. Oil Chem. Soc., 88: 559-562.
- Boehman A, Alam M (2003). Fuel formulation effects on diesel fuel injection, combustion, emissions, and emission control. Proceedings of DOE 2003, Diesel Engine Emissions Reduction Conference, Newport, RI, pp: 1-9.
- Breda K (2006). Experimental Investigation of Optimal Timing of the Diesel Engine Injection Pump using Biodiesel Fuel. Energy Fuels, 20: 1460-1470.
- Brown GW, McCallion H (1967-68). Simulation of an injection system with delivery pipe cavitation using a digital computer, Proc. Inst. Mech. Eng., 182(3L): 206-216.
- Bryan RM (2009). Biodiesel production, properties and feed stocks: Invited Review, *In vitro Cell Dev. Biol. Plant*, 45: 229-266.
- Gerpen JV (2003). Biodiesel production and Fuel Quality University of Idaho, Moscow, pp. 1-12.
- Gerpen JV, Shanks BR, Knothe G (2004). Biodiesel analytical methods, National Renewable Energy Laboratory, p. 95.
- Gerpen JV, Shanks B, Pruszko, Clements R, Knothe G (2004). Biodiesel analytical methods, National Renewable Energy Laboratory, p. 95.
- Giffen E, Rowe AW (1939). Pressure calculations for oil engine fuel injection system. Proc. Inst. Mech. Eng., 142: 519-534.
- Heinrich P, Manfred W, Josef R (1999), Technical Performance of Vegetable Oil Methyl esters with a High Iodine Number, 4<sup>th</sup> Biomass Conference of the Americas. BLT Wieselburg Australia, pp: 1-6.
- Heywood JB (1988). Internal Combustion Engine Fundamentals, McGraw-Hill, Inter. New York, pp: 586-592.
- Jindal S, Bhagwati PN, Narendra SR (2010). Comparative Evaluation of Combustion, Performance and Emissions of *Jatropha* Methyl Ester and Karanja Methyl Ester in a Direct Injection Diesel Engine, Energy Fuels, 24: 1565-1572.
- Jo-Han Ng, Hoon KN, Suyin G (2010). Advances in biodiesel fuel for application in compression ignition engines, Clean Technol. Environ. Policy, 12: 459-493.
- Kalbande SR, More GR, Nadre RG (2008). Biodiesel Production from Non-edible Oils of *Jatropha* and Karanj for utilization in Electrical Generator, Bioenerg. Res., 1: 170-178 .
- Knothe G (2010). Biodiesel: Current Trends and Properties, Top Catal, 53: 714-720.
- Kumar A, Sharma S (2008). An evaluation of multipurpose oil seed crop for industrial uses (*Jatropha curcas* L.): A review, Ind. Crops. Prod., 28(1): 1-10.
- Lebedevas S, Vaicekauskas A (2004). Improvement of the parameters of maintenance of medium speed diesels applying the motor methods, Transport, XVI(6): 252-261.
- Meher LC, Naik SN, Das LM (2004). Methanolysis of *Pongamia pinnata* (Karanja) oil for production of biodiesel. J. Sci. Ind. Res.,

- 63: 913-918
- Mitra CR (1963). Development of Minor and Non-edible Oils, Report of the Indian Central Oilseeds Committee, Hyderabad, p. 29.
- Myo T (2008). The Effect of Fatty Acid Composition on the Combustion Characteristics of Biodiesel. Doctoral Dissertation, Graduate School of Science and Engineering, Kagoshima University, Doctorate, p. 273.
- Naik M, Meher LC, Naik SN, Das LM (2008). Production of Biodiesel from high free fatty acid Karanja (*Pongamia pinnata*) oil. Biomass and Bioenergy, 32:354-357.
- Obert EF (1973). Internal combustion engines and air pollution, Harper International edition (3/e). Harper and Row Publishers, Inc: pp.451-453.
- Pulkrabek WW (2003). Engineering Fundamentals of the Internal Combustion Engine, McGraw-Hill Inc., New York.
- Rao PV (1993). Pressure-Time Analysis of a Unit Injector, A Thesis submitted to the Indian Institute of Science. Bangalore, India, pp: 6-9
- Robert L, McCormick, Michael S, Grab ski, Teresa L, Alleman, Andrew MH, Shaine TK (2001). Impact of Biodiesel Source Material and Chemical Structure on Emissions of Criteria Pollutants from a Heavy-Duty Engine. Environ. Sci. Technol., 35: 1742-1747.
- Romulo DA, Andrade, Elaine A, Faria, Amaury M, Silva, Wandallas C, Araujo, Gustavo C, Jaime, Kenia PC, Alexandre GS, Prado (2011). Heat of combustion of biofuels mixed with fossil diesel oil. J. Therm. Anal. Calorim, Springer: s10973-011-1408-x. <http://www.springerlink.com/content/j30165672m014128/fulltext.pdf>
- Sanaz S, Ngoh GC, Rozita Y (2010). An Overview on Transesterification of Natural Oils and Fats, Biotechnology and Bioprocess Engineering 15:891-904.
- Tapasvi D, Wiesenborn D, Gustafson C (2005). Process Model for Biodiesel Production from various Feedstock's, Trans. ASAE, 48(6): 2215- 2221.
- Vivek, Gupta AK (2004). Biodiesel production from Karanja oil. J. Sci. Ind. Res., 63: 39-47.
- Yamane K, Ueta A, Shimamoto Y (2001). Influence of Physical and Chemical Properties of Biodiesel Fuel on Injection, Combustion and Exhaust Emission Characteristics in a DI-CI Engine" Tran. Of the Jap. Soc. Mech. Eng., 32(2): 25-30.