THE EFFECTS OF ETHANOL ADDITION WITH WASTE PORK LARD METHYL ESTER ON PERFORMANCE, EMISSION, AND COMBUSTION CHARACTERISTICS OF A DIESEL ENGINE

by

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In the recent research, as a result of depletion of world petroleum reserves, considerable attention has been focused on the use of different alternative fuels in diesel engines. The present work aims to ensure the possibility of adding ethanol as an additive with animal fat biodiesel that is tested as an alternative fuel for diesel in a compresion ignition engine. In this study, biodiesel is obtained from waste pork lard by base-catalyzed transesterification with methanol when potassium hydroxide as catalyst. 2.5%, 5%, and 7.5% by volume of ethanol is blended with neat biodiesel in order to improve performance and combustion characteristics of a diesel engine. The experimental work is carried out in a 3.7 kW, single cylinder, naturally aspirated, water cooled, direct injection diesel engine for different loads and at a constant speed of 1500 rpm. The performance, emission, and combustion characteristics of biodiesel-ethanol blends are investigated by comparing them with neat biodiesel and standard diesel. The experimental test results showed that the combustion and performance characteristics improved with the increase in percentage of ethanol addition with biodiesel. When compared to neat biodiesel and standard diesel, an increase in brake thermal efficiency of 5.8% and 4.1% is obtained for BEB7.5 blend at full load of the engine. With the increase in percentage of ethanol fraction in the blends, peak cylinder pressure and the corresponding heat release rate are increased. Biodiesel-ethanol blends exhibit longer ignition delay and shorter combustion duration when compared to neat biodiesel. Optimum reduction in carbon monoxide, unburned hydrocarbon, and smoke emission are attained while using BEB5 blend at full load of the engine. However, there is an adverse effect in case of nitrogen oxide emission.

Keywords: *diesel engine, biodiesel, ethanol, waste pork lard methyl ester, engine performance, exhaust emissions, combustion*

Introduction

The energy needs of the world increases due to rapid decrease in world petroleum reserves, increase in the prices of conventional petroleum fuels and restrictions on exhaust emissions from diesel engines. The increase in energy demand and the depletion of oil reserves necessitate the focus on the use of various alternative fuels in internal combustion engines. An alternative to diesel fuel needs to be technically feasible, economically competitive, environmentally feasible, and easily available. Biodiesel is a significant alternative fuel which consists

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of alkyl esters of fatty acids derived from vegetable oils and animal fats. Physical characteristics of biodiesel are very similar to that of conventional diesel fuel [1]. Many investigations have shown that using biodiesel in diesel engines can reduce hydrocarbon, carbon monoxide, and particulate matter emissions with an increase in nitrogen oxide emission [2-4]. Gattamaneni *et al.* [5] investigated combustion and emission characteristics of a diesel engine fuelled with rice bran oil (RBO) methyl ester and its blends with diesel fuel. The results showed that the ignition delay and peak heat release rate for RBO methyl ester blends were lower than that of diesel fuel and ignition delay decreased with increase in percentage of RBO methyl ester in the blend. The brake thermal efficiency, HC, CO, and soot concentration were reduced whereas NO_x emissions were slightly increased with the addition of RBO methyl ester in diesel. Dhananjaya *et al.* [6] investigated combustion characteristics of a diesel engine fuelled by jatropha methyl ester for different fuel injection timings and at rated injector opening pressure of 220 bar. They concluded that fuel injection timing of 26° bTDC was found to be optimum for B20 fuel for performance and emissions. Sahoo *et al*. [7] investigated with jatropha, karanja, and polanga biodiesel in a diesel engine. They reported an increase in peak cylinder pressure and decrease in ignition delay for all biodiesels when compared to standard diesel. Godiganur *et al*. [8] tested methyl ester of karanja oil in a Kirloskar HA394DI diesel engine. From their investigation, maximum brake thermal efficiency of 31.28% was obtained with B20 biodiesel blend at full load of the engine, which was higher than that of standard diesel. The brake specific energy consumption for B20 blend was lower than that of diesel fuel at full load, however for other biodiesel blends there was an increasing trend of BSEC. The reduction in CO and HC emission was obtained with all biodiesel blends but there was an adverse effect in case of NO_x.

Biodiesel obtained from animal fats has high cetane number, rich oxygen content and very close lower heating values when compared to standard diesel. Hence, it is preferred as the best alternative for biodiesel production [9]. Animal fats offer the advantage of freely mixing with alcohols (both methanol and ethanol) and the obtained blends can be used in existing diesel engines without any engine modifications [10]. The direct use of animal fats in diesel engines without pretreatment or engine modification causes serious engine problems. Different methods have been considered to reduce the viscosity of animal fats such as preheating, blending, pyrolysis, micro-emulsion, catalytic cracking, and transesterification. Out of these, the transesterification is a widely accepted, convenient, and most promising method for reduction of viscosity and density of animal fats. A detailed description of the transesterification process can be found in the literature [11-14].

A lot of research work has been carried out to use ethanol in compression ignition engine. Ethanol is a low cost oxygenated compound with high oxygen content (34.8%). It is a biomass based renewable fuel that can be produced from vegetable materials such as corn and sugarcane and it is expected to improve low temperature flow properties. The use of ethanol in diesel engines has received a considerable attention in the recent years. Kumar *et al*. [10] discussed the ethanol-animal fat emulsions in a diesel engine and compared the performance and emission analysis with neat fat. The results showed that there was a drastic reduction in CO, HC, NO_x, and smoke emissions, when compared to neat fat and neat diesel at higher loading conditions. A study on the performance and emission characteristics of a diesel engine fuelled with rice bran biodiesel and ethanol blends reported that the brake thermal efficiency of 2.5% ethanol blended rice bran biodiesel increases by 6.98% and 3.93%, respectively, when compared to diesel fuel and biodiesel. Carbon monoxide, hydrocarbon, unused oxygen and smoke emission were decreased by 17.39%, 62.2%, 14.4%, and 27.4%, respectively, for 2.5% ethanol blend when compared to standard diesel [15]. Sivalakshmi *et al*. [16] investigated ethanol addition on a diesel engine fuelled with neem oil methyl ester. They concluded that peak cylinder pressure and peak heat release rate was higher for ethanol blended biodiesel. There was an improvement in brake thermal efficiency for all loads with the addition of ethanol to biodiesel. The smoke intensity and CO emissions were found to be lower at higher loads with the addition of ethanol to neem oil methyl ester. Zhu *et al.* [17] investigated combustion, performance, and emission characteristics of a direct injection diesel engine fueled with ethanol-biodiesel blends. In their research work, biodiesel was produced from waste cooking oil. The results indicated that when compared to neat biodiesel, the combustion characteristics of ethanol-biodiesel blends changed. For biodiesel-ethanol blends, the maximum cylinder pressure and heat release rate increased with increase of ethanol fraction in the blended fuel. Brake thermal efficiency of BE5 biodiesel-ethanol blend was slightly higher than that of neat biodiesel. Compared to neat biodiesel, BE5 gave slightly lower BSCO and BSHC emissions in all test modes. Aydin *et al.* [18] investigated the effect of ethanol blending with biodiesel on engine performance and exhaust emissions in a compression ignition (CI) engine. In their study, they tested the engine with diesel fuel, B20 biodiesel blend and BE20 biodiesel-ethanol blend. The experimental results showed that the performance of a CI engine improved with the use of BE20 when compared to B20. The exhaust emissions for BE20 were fairly reduced.

This research work aims to investigate the effects of ethanol addition with waste pork lard methyl ester (animal fat biodiesel) on performance, emission and combustion characteristics of a direct injection diesel engine. The experimental work is carried out by using biodiesel-ethanol blends and the results are compared with neat biodiesel and standard diesel.

Biodiesel production and its properties

In this research study, biodiesel is produced from waste pork lard by transesterification process. The standard diesel is purchased from Indian oil corporation company fuel supply station (which is operated by Government of India) and waste pork lard is collected from a slaughterhouse in Tamil Nadu, India. Esterification of waste pork lard is composed of heating of oil (melted animal fat oil), addition of potasium hydroxide and methyl alcohol, stirring of mixture, separation of esters and glycerol, washing esters with distilled water and heating for removal of water. This process produces uniform quality of alkyl esters (methyl esters of waste pork lard) and reduces viscosity and increases cetane number. In a transesterification reaction, the following parameters should be taken into account: water in the reagents, molar ratio of reagents, concentration of free fatty acids in oils, temperature, the reaction time, types of alcohol, and types of

Table 1. The properties of standard diesel, neat biodiesel, ethanol, and biodiesel-ethanol blends

Property	ASTM method	Diesel	Biodiesel [B100]	Ethanol	BEB 2.5	BEB 5	BEB 7.5
Flash point [°C]	D93	58	159.5	13.5	156	153	142
Kinematic viscosity at 40°C [mm^2s^{-1}]	D445	2.85	5.26	1.2	4.92	4.51	4.13
Density at 20 °C [kgm^{-3}]	D1298	842.5	873.2	789	869	862	858
Calorific value [$MJkg^{-1}$]	D240	43.4	39.85	27	39.6	39.2	38.7
Cetane index	D976	47	59	8	56	53	49
Carbon content [% mass]	D5291	86.7	76.1	52.2	76.0	74.8	73.7
Hydrogen content [% mass]	D5291	12.8	12.7	13	12.1	12.2	12.2
Oxygen content [% mass]	D5291	–	11.2	34.8	11.9	13.0	14.1

catalysts. The properties of diesel, biodiesel and biodiesel-ethanol blends are shown in tab.1. Density and kinematic viscosity of biodiesel is higher than that of standard diesel. The calorific value of biodiesel is 8.2% lower than that of standard diesel and 32.3% higher than that of ethanol. As seen in tab.1, while ethanol concentration increases in the blends increase oxygen content and decrease cetane number.

Experimental set-up and procedure

A stationary type, single cylinder, four stroke, direct injection, naturally aspirated, water cooled, Kirloskar make, AV1 model diesel engine is used in this study. The schematic diagram of the experimental set-up is shown in fig. 1. Technical specifications of the engine are shown in tab. 2. The fuels used in this study include standard diesel, neat biodiesel, and biodiesel-ethanol blends at different engine loads from 0% to 100% exactly with an incremental steps of 20%. Before running the engine with new fuel, it is allowed to run for sufficient time to consume the remaining part of fuel from the previous experiment. The engine is started initially with standard diesel and warmed to obtain its base parameters. Then, the same tests are performed with neat biodiesel and its ethanol blends. When the engine reaches the stabilized working condition, parameters like fuel consumption and load are measured. Fuel consumption is measured with a burette (20 ml volume) and a stopwatch.

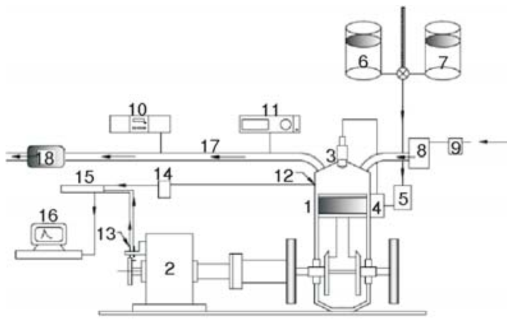

Figure 1. The experimental set-up
1 – Kirioskar AV1 engine, 2 – eddy current dynamometer, 3 – injector, 4 – fuel pump, 5 – fuel filter, 6 – diesel tank, 7 – biodiesel tank, 8 – air stabilizing tank, 9 – air filter, 10 – AVL smoke meter, 11 – AVL Di-gas analyser, 12 – pressure transducer, 13 – TDC encoder, 14 – charge amplifier, 15 – indimeter, 16 – monitor, 17 – exhaust pipe line, 18 – exhaust silencer

Table 2. Technical specifications of the engine

Particulars	Specification
Make and model	Kirloskar, AV1
Method of cooling	Water cooled
Number of cylinders	One
Rated power	3.7 kW [5HP]
Rated speed	1500 rpm
Combustion system	Direct injection
Bore/stroke	80 mm /110 mm
Engine displacement	0.553 litre
Compression ratio	17.5 : 1
Fuel injection timing	23° bTDC
Fuel injection pressure	220 bar
Loading device	Eddy current dynamometer

The performance parameters of neat biodiesel (B100) and its ethanol blends (BEB2.5, BEB5, and BEB7.5) are determined in comparison with baseline. Similarly exhaust emissions like carbon monoxide (CO), unburned hydrocarbon (HC), and nitrogen oxide (NO_x) are measured using a non-dispersive infra-red analyzer (NDIR) (Make: AVL-444 Di-gas analyzer) and smoke density is measured with an AVL 437C smoke meter. A Kistler piezoelectric transducer (Type 6056A) is installed at the cylinder head in order to measure cylinder pressure (average for 100 working cycles). The signals from pressure transducer are amplified with a Kistler charge amplifier (Type 5011B) and analyzed with a combustion analyzer to obtain the heat release rate. A high precision crank angle encoder is employed for TDC and crank angle signal acquisition. The test engine is loaded with an eddy current dynamometer and load on the dynamometer is measured using a strain gauge sensor. The specification of exhaust gas analyzer, smoke meter, and calculated uncertainty values are tabulated tab. 3 and tab. 4.

Table 3. Exhaust gas analyzer and smoke meter specification

Gas analyzer model – AVL Digas 444		
Pollutant	Range	Accuracy
CO	0-10 vol.%	0.01
HC	0-20000 ppm	+10 ppm
NO_x	0-5000 ppm	+10 ppm
Smoke meter model – AVL 437C		
Smoke intensity	0-100 opacity [%]	+1% full scale reading

Table 4. Uncertainties of instrumentation

Parameter	Percentage error
Kinematic viscosity	±1.4%
BTE	±2.5% max
CO	±0.01%
HC	±1 ppm
NO_x	±1 ppm
Speed	±2 rpm
Load	±2 N
Smoke density	±2 HSU

Estimation of the experimental heat release rate [19]

The combustion characteristic and heat release rate based on the data of the recorded cylinder pressure are analyzed. From the first law of thermodynamics:

$$\frac{dQg}{d\theta} = \frac{dQn}{d\theta} + \frac{dQw}{d\theta} \tag{1}$$

This can be rewritten as:

$$\frac{dQn}{d\theta} = \frac{dQg}{d\theta} - \frac{dQw}{d\theta} \tag{2}$$

Thus the net heat release rate is the difference between the heat released by combustion of fuel and the heat absorbed by cylinder wall. Using the first law of thermodynamics, the net heat release rate is calculated by:

$$\frac{dQn}{d\theta} = \frac{\lambda}{\lambda - 1} P \frac{dV}{d\theta} + \frac{1}{\lambda - 1} V \frac{dP}{d\theta} \tag{3}$$

where θ is the crank angle and λ – the ratio of specific heats, C_p/C_v.

Results and discussions

Brake thermal efficiency

The variation of brake thermal efficiency (BTE) of the engine with load for different test fuels is shown in fig. 2. The brake thermal efficiency of biodiesel-ethanol blends is higher than that of standard diesel at all loading conditions. This can be attributed to better combustion of ethanol blended biodiesel, which has more oxygen content than standard diesel and

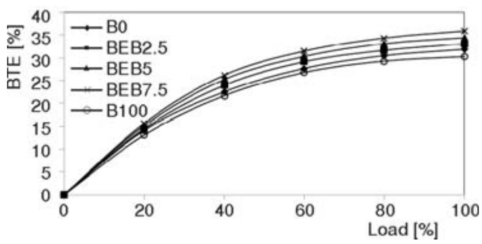

Figure 2. Variation of BTE with load for different fuels

neat biodiesel. It can be observed from fig. 2 that BTE increases with increase of ethanol percentage in biodiesel. The addition of ethanol to biodiesel will decrease viscosity of the fuel blends and cause improvement in fuel spray and atomization which in turn offers better combustion and increase in brake thermal efficiency. The increase of BTE is due to the improvement of combustion process on account of increased oxygen content in the blended fuels. The BTE of BEB7.5 blend is 35.9% which is 4.1% and 5.8% higher than that of standard diesel and neat biodiesel at full load of the engine. However, the BTE of neat biodiesel is lower than that of standard diesel at all loads and it is due to higher viscosity of neat biodiesel which leads to reduced atomization, fuel vaporization, and spray formation and hence combustion process is affected and may contribute to the increase in compression work and power loss resulting in decreased BTE [5].

Carbon monoxide emission

The variation of CO emission with load for different test fuels is shown in fig. 3. With the addition of ethanol content in the blend and at a lower load, the CO emission decreases for all blended fuels and neat biodiesel and then increases during higher loading conditions due to higher viscosity of ethanol-biodiesel blends. At high load, the CO emissions of biodiesel-ethanol blends decrease significantly when compared to standard diesel and neat biodiesel. This is due to the presence of higher oxygen content of ethanol in biodiesel. However, at low load, addition of ethanol to biodiesel ensures minimal CO emission while comparing BEB blends and standard diesel. This may be due to higher latent heat of vaporization of ethanol causing lower combustion temperature and thick quenching layer, which result in a lower CO oxidation rate. At 100% load, the percentage of reduction in CO emission for biodiesel-ethanol blends BEB2.5, BEB5, BEB7.5, and neat biodiesel B100 is 38.35%, 43.83%, 30.13% and 12.32%, respectively, which is lower than that of standard diesel. For BEB5, the CO emission is even lower than that of other test fuels and this is due to higher oxygen content and faster combustion rate which leads to the reduction of CO emission.

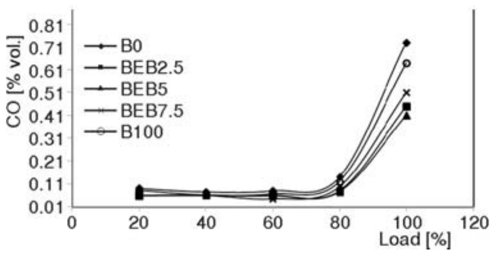

Figure 3. Variation of CO emission with load for different fuels

Hydrocarbon emission

The variation of HC emission with load for different test fuels is shown in fig. 4. It is clear that there is an increase in HC emissions for all the test fuels as load increases. This is due to fuel-rich mixtures at higher loads. Compared to standard diesel, the HC emission for BEB7.5 blend is higher during all loading conditions. This is due to the cooling effect found in high percentage of ethanol in biodiesel which reduces in-cylinder gas temperature leading to poorer oxidation reaction rate and increase in HC emissions. However for BEB2.5 and BEB5 blends, the HC emission is lower than that of

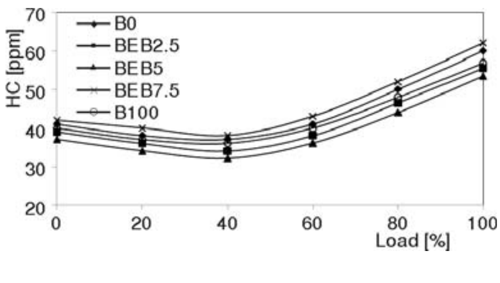

Figure 4. Variation of HC emission with load for different fuels

standard diesel and neat biodiesel. The maximum reduction in HC emission is obtained for BEB5 biodiesel-ethanol blend. This may be due to higher oxygen content and reduced viscosity of BEB5 blend, leading to improved spray and atomization, better combustion and hence lower HC emission. At 100% load, the percentage of reduction in HC emission for BEB2.5 and BEB5 blends is 7.5% and 10.83%, respectively, which is lower than that of standard diesel and neat biodiesel.

Oxides of nitrogen emission

The variation of NO_x emission with load for different test fuels is shown in fig. 5. The NO_x emission for different test fuels is in increasing trend with respect to load. The most important factors which influence the formation of NO_x are combustion temperature and availability of oxygen during combustion. It can be seen from fig. 5 that when the concentration of ethanol increases, an increasing trend of NO_x formation occurs, compared to standard diesel and neat biodiesel. The increase in NO_x emission is directly proportional to the addition of ethanol fraction in the blends. This is due to higher oxygen content of ethanol which causes better combustion in the combustion chamber, resulting in high temperature and high NO_x formation. Further, ethanol addition to biodiesel decreases cetane number significantly and causes increase in ignition delay period; thereby more fuel/air mixture is accumulated into combustion chamber which causes a rapid heat release at the beginning of the combustion, which results in high temperature and high NO_x formation [20]. The reason for increase in NO_x formation is discussed detail in chapters 4.6 (cylinder pressure) and 4.9 (heat release rate), respectively. Oxygen enriched fuel increases peak cylinder pressure and corresponding heat release rate with increase of ethanol fraction in the blends. However, NO_x emission for neat biodiesel is lower than that of standard diesel. This is due to higher cetane number and shorter ignition delay of neat biodiesel. A higher cetane number would result in a shortened ignition delay period thereby allowing less time for the air/fuel mixing before the premixed combustion phase. Consequently, a weaker mixture would be generated and burnt during the premixed combustion phase resulting in a relatively reduced NO_x formation [3]. At 100% load, the NO_x emission for biodiesel-ethanol blends BEB2.5, BEB5, BEB7.5 and neat biodiesel B100 is 614 ppm, 631 ppm, 646 ppm, and 567 ppm, respectively, whereas it is 589 ppm for standard diesel.

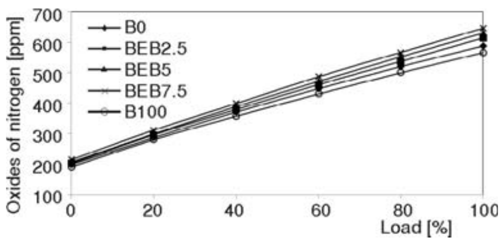

Figure 5. Variation of oxides of nitrogen emission with load for different fuels

Smoke density

The variation of smoke density with load for different test fuels is shown in fig. 6. From the figure, it is clear that there is a general trend of increase in smoke concentration as the load increases. This is due to the presence of fuel rich mixtures at higher loads. At 20% and 40% load conditions, the reduction in smoke emission for biodiesel-ethanol blends is minimum when compared to standard diesel. However at higher

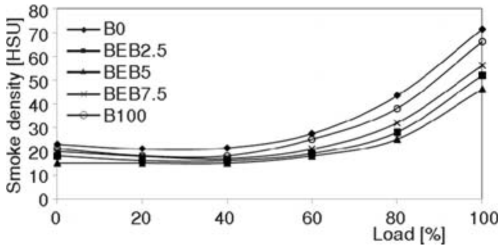

Figure 6. Variation of smoke emission with load for different fuels

loads (60%-100% load), maximum quantity of reduction in smoke emission is obtained for neat biodiesel and its ethanol blends. The addition of ethanol to biodiesel reduces cetane number of the blends and increases ignition delay allowing more time for fuel/air mixing. This will result in a less fuel-rich mixture for the premixed combustion phase and it may be the reason for reduction in smoke concentration for ethanol blended fuels. At 100% load, the percentage of reduction in smoke emission for biodiesel-ethanol blends BEB2.5, BEB5, BEB7.5, and neat biodiesel B100 is 27.28%, 35.66%, 21.67%, and 7.69%, respectively, which is lower than that of standard diesel. The maximum reduction in smoke emission is obtained for BEB5 biodiesel-ethanol blend. This may be attributed to the engine running with overall "lean mixture" with the combustion being assisted by the presence of fuel-bound oxygen of ethanol even in locally rich zones [21].

Cylinder pressure

The cylinder pressure variation (average for 100 working cycles) of standard diesel, neat biodiesel and biodiesel-ethanol blends at 100% load is shown in fig. 7. In a CI engine, the cylinder pressure characterizes the ability of the fuel to mix well with air and burn. It is clear from fig. 7 that when the concentration of ethanol increases in the blends, compared to standard diesel, higher cylinder pressure is obtained for all BEB blends. This is due to lower cetane number and longer ignition delay period of ethanol blends. At lower engine loads (not shown), a very small quantity of fuel is injected into combustion chamber and combustion starts after TDC for standard diesel. However, at higher engine loads, due to the longer ignition delay of ethanol blended fuels, a larger amount of fuel is accumulated in combustion chamber during the premixed combustion phase leading to a higher peak cylinder pressure and heat release rate. While using BEB2.5 and BEB5 blends, the combustion starts at almost the same crank angle, which may reflect that the ignition delays of BEB2.5 and BEB5 are similar to that of neat biodiesel. As shown in fig. 9, at 100% load, the peak cylinder pressure for biodiesel-ethanol blends BEB2.5, BEB5, and BEB7.5 is 66.3 bar, 66.95 bar, and 67.29 bar, respectively, which is higher than that of standard diesel and neat biodiesel.

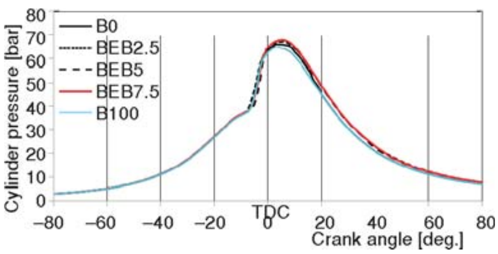

Figure 7. Variation of cylinder pressure at full load for different fuels
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Combustion duration

The variation of total duration of combustion with load for different test fuels is shown in fig. 8. The combustion duration is defined as duration between 5% after the start of combustion and 95% before the end of heat release. Combustion duration increases with an increase in engine load owing to accumulation of more fuel being injected into the combustion chamber. The combustion duration of ethanol blended fuels is found to decrease with the in-

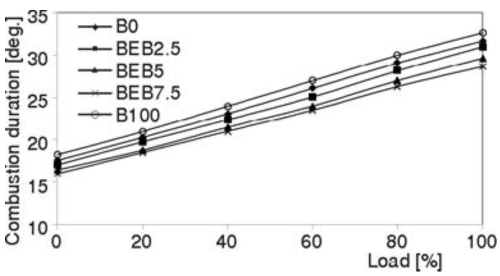

Figure 8. Variation of combustion duration with load for different fuels

crease in proportionate quantity of ethanol in neat biodiesel. This is due to higher oxygen content of ethanol in the blend and faster rate of combustion. It is observed from fig. 8 that the combustion duration of neat biodiesel is higher than that of other test fuels. It is due to lower calorific value of waste pork lard methyl ester which requires more amount of fuel to be injected into the combustion chamber in order to maintain the engine speed stable for different loading conditions. At 100% load, the combustion duration for standard diesel (B0), neat biodiesel (B100), biodiesel-ethanol blends BEB2.5, BEB5, and BEB7.5 is 31.69° CA, 32.64° CA, 31.02° CA, 29.63° CA, and 28.67° CA, respectively.

Ignition delay

The variation of ignition delay with load for different test fuels is shown in fig. 9. The ignition delay period of the test fuels decreases with increase in engine load condition. It is observed from fig. 9 that the ignition delay period of biodiesel-ethanol blends is higher than that of standard diesel and neat biodiesel at all engine loads. Further, ignition delay increases with increase in percentage of ethanol in the blends at all loads. This is due to lower cetane number and high latent heat of vaporization of ethanol that causes lower in-cylinder temperature and increase in ignition delay [22]. However, the ignition delay period of neat biodiesel is lower than standard diesel and ethanol blended fuels. This is due to the presence of more oxygen content and higher cetane number of neat biodiesel which improves ignitability. As a result of high cylinder temperature existing during fuel injection, biodiesel undergoes thermal cracking to produce lighter compounds, which may have ignited earlier to result in a shorter ignition delay [23]. At 100% load, the ignition delay period of biodiesel-ethanol blends BEB2.5, BEB5, and BEB7.5 is 9.78° CA, 10.14° CA, and 10.24° CA, respectively, which is higher than that of standard diesel and neat biodiesel.

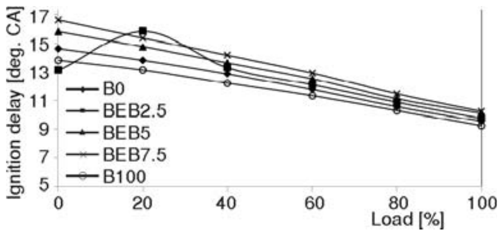

Figure 9. Variation of ignition delay with load for different fuels

Heat release rate

The variation of heat release rate with crank angle at 100% engine load for standard diesel, neat biodiesel, and biodiesel-ethanol blends is shown in fig. 10. During ignition delay period, due to heat loss from the cylinder and cooling effect of ethanol blended fuel vaporizing (as it is injected into the cylinder), ensure slight decrease in heat release rate and then a rapid increase in the premixed combustion phase. After this phase, the combustion continues slowly until most of the fuel is burned. It can be seen from fig. 10 that, at the same operating condition, the heat release rate of all biodiesel-ethanol blends is higher than that of standard diesel and neat biodiesel. Further, the heat release rate increases with the increase of ethanol fraction in the blended fuel. Because of the lower cetane number of ethanol, the start of combustion is retarded, leading to more fuel combusted in the premixed phase resulting in higher cylinder

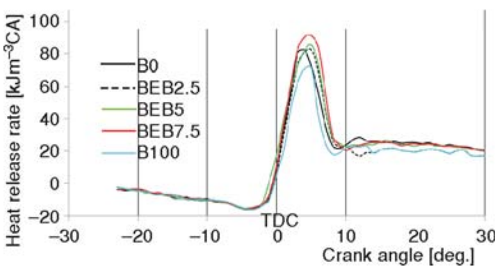

Figure 10. Variation of heat release rate at full load for different fuels
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pressure and higher premixed heat release rate [24, 25]. The heat release rates of all the fuels have similar shape with a premixed combustion phase followed by a diffusion combustion phase. It can be found that the premixed combustion phase for all the fuels is shortened, while the diffusion combustion is lengthened, with the increase of engine load. The peak heat release rate is higher for BEB7.5 blend. This may be due to higher volatility and better mixing of ethanol blended fuel with air. As the engine load is increased, the heat release rate of ethanol blended fuels is higher because of the longer ignition delay, during which more fuel is accumulated in the combustion chamber to release higher heat during the premixed combustion phase. On the other hand, the peak heat release rate is lower for neat biodiesel when compared to standard diesel. This may be due to lower volatility and higher viscosity of neat biodiesel, which leads to a reduction in air entrainment and fuel-air mixing rates, resulting in lesser amount of fuel being prepared for premixed combustion stage during ignition delay [19]. At 100% load, the heat release rate of standard diesel (B0), neat biodiesel (B100), biodiesel-ethanol blends BEB2.5, BEB5, and BEB7.5 is 72.24, 71.65, 82.65, 85.58, and 91.46 kJm^{-3}°CA, respectively.

Conclusions

This research work focused on the suitability of adding ethanol to methyl esters of waste pork lard (animal fat biodiesel), which is substituted as an alternative to diesel in a CI engine. The performance, emission and combustion characteristics of a single cylinder direct injection diesel engine are investigated using methyl esters of waste pork lard and its ethanol blends and compared with that of standard diesel. Based on the experimental study, the key results are summarized as follows.

- Addition of ethanol to biodiesel has shown an improvement in brake thermal efficiency at all engine loads. The maximum BTE of BEB7.5 blend is 35.9%, which is 5.8% and 4.1% higher than that of neat biodiesel and standard diesel at full load of the engine.
- For biodiesel-ethanol blends, the exhaust emissions like CO, HC, and smoke concentration are lower than that of standard diesel and neat biodiesel at rated load. The optimum reduction in CO, HC, and smoke emission is obtained for BEB5 biodiesel-ethanol blend. Hydrocarbon emission becomes slightly higher by adding a higher percentage of ethanol to biodiesel at all engine loads. There is an adverse effect in case of NO_x emission for all biodiesel-ethanol blends.
- The peak cylinder pressure and corresponding peak heat release rate for biodiesel-ethanol blends are found to be higher than that of standard diesel. The peak heat release rate is increased from 82.65 kJm^{-3}°CA to 91.46 kJm^{-3}°CA for BEB2.5 and BEB7.5. The peak heat release rate of BEB7.5 blend has maximum value than other test fuels.

On the whole, methyl esters of waste pork lard and its ethanol blends can be used as an alternative fuel in diesel engines without any engine modifications. Higher percentage of ethanol addition with animal fat biodiesel increases peak cylinder pressure, heat release rate and BTE of the engine. Lower percentage of ethanol addition results an appreciable amount of reduction in CO, HC, and smoke emission when compared to neat biodiesel and standard diesel.

Acronyms

BEB2.5 – 2.5% ethanol + 97.5% biodiesel by volume
BEB5 – 5% ethanol + 95% biodiesel by volume
BEB7.5 – 7.5% ethanol + 92.5% biodiesel by volume
BE5 – 5% ethanol + 95% biodiesel by volume
BE20 – 20% ethanol + 80% biodiesel by volume
BSCO – brake specific carbon monoxide
BSEC – brake specific energy consumption

BSHC – brake specific hydrocarbon
bTDC – before top dead centre
BTE – brake thermal efficiency
B20 – 20% biodiesel + 80% diesel fuel by volume
B100 – neat biodiesel
HSU – Hatridge smoke unit
RBO – rice bran oil
rpm – revolution per minute
TDC – top dead centre

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