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Comparison of Performance and Emission Parameters of a Diesel Engine Fueled with Biodiesel and Wood Pyrolysis Oil Emulsions

R. Prakash*[1], R.K. Singh[#] and S. Murugan*

Abstract – *Woody biomass is largely available and can be converted into useful energy through direct combustion, pyrolysis and gasification. Wood pyrolysis oil (WPO) has a poor miscibility with diesel fuel. WPO also exhibits carbon deposit, valve sticking etc when WPO is used in the form of emulsion with ignition improver in compression ignition engines. Preliminary investigations revealed that WPO can be emulsified with biodiesel to some extent. This paper describes the comparative study of the performance and emission characteristics of a single cylinder, 4-stroke, air cooled, direct injection diesel engine fueled with two different emulsions made from (i) methyl ester of karanja (KME) and (ii) methyl ester of jatropha (JME) with WPO. The surfactant used to get the emulsion was Span20 at 2% by volume. The percentages of WPO in the emulsion were 10 and 15% by volume. The emulsions prepared with KME-WPO and JME-WPO are denoted as KOE10, KOE15, JOE10 and JOE15 respectively. The results were compared with diesel fuel operation and presented in this paper.*

Keywords – Biodiesel, bio-oil, diesel engine, performance, emissions.

1. INTRODUCTION

Energy sources are classified as renewable and non-renewable. Energy obtained by hydro, solar, wind, biomass and wastes are renewable energy sources, while fossil fuels are non-renewable energy sources [1]. The issues of energy availability and its security have caused serious concerns around the world, and prompted researchers to look for better alternatives to reduce the dependency on petroleum products. Fossil fuels have a negative effect on environment, by emitting CO_2, CO, SOx , NOx and smoke emissions when used as fuel in combustion devices. NOx and CO_2 cause greenhouse effect and SOx cause acid rains [2]. Bio fuels produced from lignocellulosic materials and vegetable oils provide a feasible solution to the twin crises of fossil fuel depletion and environmental degradation. Biodiesel is considered as a promising alternative fuel for diesel engines. It is an oxygenated fuel made from vegetable oils and animal fats by the conversion of the triglycerides to esters (primarily methyl esters) via various esterification processes [3]. The fuel characteristics of biodiesel are similar to that of fossil diesel fuel and it permits the biodiesel to use as an alternative fuel for diesel engines without any major modification. Its additional advantages include outstanding lubricity, excellent biodegradability, superior combustion efficiency and low toxicity, among other fuels [4]. Many studies show that unburned hydrocarbons (HC), carbon monoxide (CO) and sulfur levels are significantly less in the exhaust gas, while using biodiesel as fuel. However, a noticeable increase in the oxides of the nitrogen (NOx) levels is reported with biodiesel [5]-[8].

Jatropha and karanja are considered as the two major feed stocks in India for biodiesel production because of their availability, higher oil yield and also they are non-edible. Although biodiesel is considered as a potential alternative fuel, it has some demerits like poor cold flow properties and lower oxidation stability than petroleum fuels [9], [10]. Saturated compounds are responsible for the unfavorable cold flow properties observed in biodiesel, and the unsaturated esters are mainly responsible for the reduced oxidation stability [10]. Treatment with oxidation inhibitors containing hindered phenols is the most common approach to increase the oxidative stability of biodiesel.

Bio-oil produced from the pyrolysis of biomass sources are also considered as alternative fuels for diesel engines. Bio-oil is obtained from the condensation of biomass derived pyrolytic vapors, which are produced from the thermal degradation of biomass substances (cellulose, hemicellulose, and lignin) [11]. Bio-oil can be used for power generation [12]; however their high acidity, low thermal stability, low calorific value, high viscosity, and poor lubrication characteristics limit their use as transportation fuel. Therefore, instead of using the bio-oil as transportation fuel, it is suggested that they can be used as additives or extenders for transportation fuel in diesel vehicles. Bio-oil obtained from the pyrolysis of biomass sources contains many hindered phenols [13] known to be good anti-oxidants [14]. Bio-oil also contains nano-particles of oligomeric materials, which could serve as nucleation centers modifying the crystallization behavior of some biodiesel fractions [15]. It is also reported that the pH value of the bio diesel is reduced when it is blended with pyrolysis oil.

Wood pyrolysis oil (WPO) cannot be blended with diesel fuel, because of its poor miscibility. It doesn't disperse in diesel fuel because of its different surface tension and hydroscopic nature [16]. Several methods of

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*Department of Mechanical Engineering, National Institute of Technology, Rourkela, Orissa, 769 008, India.

[#] Department of Chemical Engineering, National Institute of Technology, Rourkela, Orissa, 769 008, India.

[1] Corresponding author; Tel: + 918895343319.
E-mail: prakasu2000@yahoo.com.

using WPO in diesel engines have been discussed by various researchers [17]-[20]. Out of these, the emulsification method described by Ikura *et al.* [20] avoids the problem of the miscibility of WPO with diesel fuel. Surfactants can be used to make emulsions with two different density liquids by reducing their surface tension. Earlier investigations carried out by the authors have proved that WPO can be emulsified with biodiesel to some extent.

Engine experiments were performed by using emulsions prepared with karanja methyl ester (KME) and WPO as well as jatropha methyl ester (JME) and WPO. Improved engine performance and simultaneous reduction of NO and smoke emissions were reported with biodiesel WPO emulsions [21]-[22]. This paper describes the comparative study of the performance and emission characteristics of a single cylinder, 4-stroke, air cooled, direct injection diesel engine fueled with two different emulsions made from KME and JME with WPO. The surfactant used to get the emulsion was Span20 at 2% by volume. The percentages by volume of WPO in the emulsion were 10 and 15%. The results were compared with diesel fuel operation and presented in this paper.

2. EXPERIMENTAL ANALYSIS

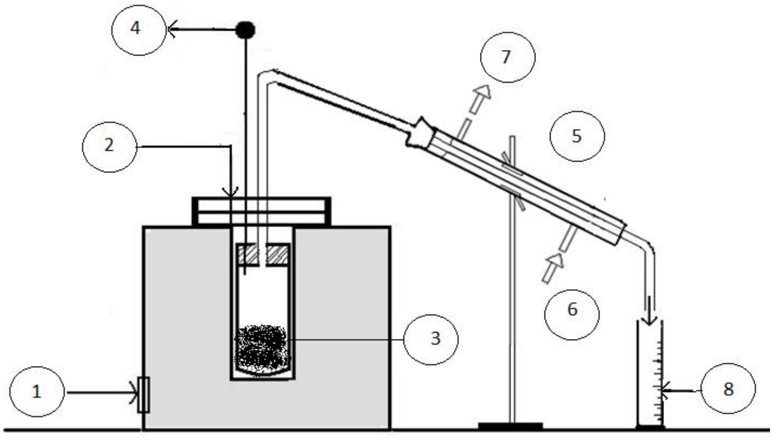
2.1 Production of Wood Pyrolysis Oil

The bio-oil used in this investigation was obtained from pine wood feed stock, available in the packing container boxes. The ultimate and proximate analysis of pine wood feed stock is given in Table 1. The feed stock was cut into small pieces and fed in to the stainless steel pyrolysis reactor. It was a slow pyrolysis process with a heating rate of 10° per minute. The optimum yield of the pyrolysis oil was obtained at the temperature ranges between 450°C and 500°C. The optimum yield obtained was around 60%. The schematic diagram of the pyrolysis setup is shown in Figure 1.

The pyrolysis oil obtained was characterized to find the physical properties and elemental composition. Table 2 shows the main components present in the WPO obtained from GC-MS analysis.

Table 1. Ultimate and proximate analysis of pine wood.

Proximate analysis	wt (%)	Ultimate analysis	wt (%)
Water content	3.00	C	50.15
Volatile matter	77.00	H	5.41
Fixed carbon	11.00	N	0.06
Ash content	9.00	O	44.37



1. Furnace 2. Reactor 3. Feed material
4. Temperature controller 5. Condenser 6. Water inlet
7. Water outlet 8. Pyrolysis oil collector

Fig.1. Schematic diagram of the pyrolysis set-up.

Table 2. Main components obtained from GC-MS analysis.

Area %	Compound Name
4.86	3-Methlcyclopentane-1,2-dione
7.24	0-Methoxyphenol
3.17	1-hydroxy-2-methoxy-4-methylbenzene
4.63	1-hydroxy-2-methoxy-4-ethylbenzene
15.29	1,3-Dimethoxy-2-hydroxybenzene
3.98	1,2,4-Trimethoxybenzene
4.58	(E)-Isoeugenol
7.34	1,2,3-Trimethoxy-5-methylbenzene
4.48	2,6-Dimethoxy-4-(2-Propenyl)Phenol
4.59	N-Methylene-1,2-diphenylethanamine
2.78	1-(2,6-Dihydroxy-4-methoxyphenyl)-1-butanone
6.65	n-Hexadecanoic acid
16.70	Oleic Acid

The analysis shows that the pyrolysis oil contents like Oleic acid, 3-Dimethoxy-2-hydroxybenzene, methoxyphenol are large in proportion. Most of the components identified are the phenols with ketones and aldehydes groups attached, and nearly all the functional groups showed the extensive existence of the oxygen. Existence of abundant aldehydes and ketones make the pyrolysis oil hydrophilic and hydrated in nature, which makes the separation of water from pyrolysis oil difficult [16]. These phenols present in the WPO will improve the oxidation stability of the biodiesel fuels.

2 .2 *Preparation of Biodiesel Emulsions with WPO*

KME and JME were produced in two stages; acid Esterification followed by transesterification process. Sulphuric acid (H_2SO_4) was used as catalyst in the acid esterification whereas sodium hydroxide (NaOH) was used as a catalyst in the transesterification process. The conversion of vegetable oil (Triglyceride esters) to methyl esters through transesterification process reduces the viscosity and increases the volatility. In this investigation, karanja oil/jatropha oil was mixed with methanol and NaOH. The mixture was heated and maintained at 65oC for one hour, while heating, the solution was stirred continuously with stirrer. Two distinct layers were formed, the lower layer was glycerin and the upper layer was ester. The upper layer was separated with moisture and the moisture content in the methyl ester has been removed by adding silica gel crystals. The properties of WPO compared with diesel, KME, JME and KME/JME emulsions with WPO are given in Table 3.

Table 3. Properties of WPO compared with diesel, KME, JME and emulsions.

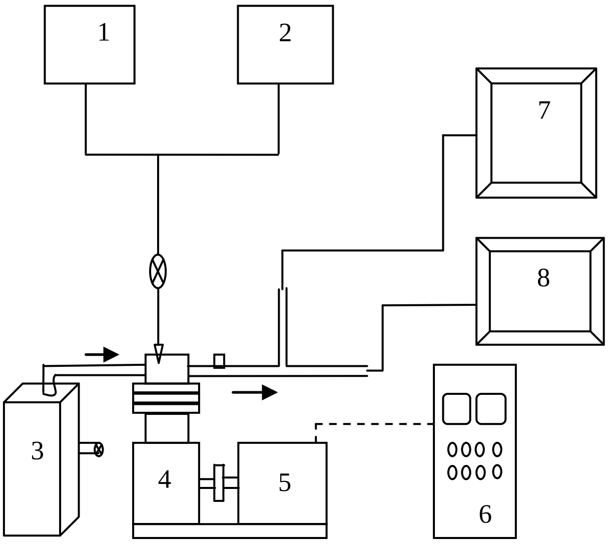
Properties	ASTM method	Diesel	WPO	KME	JME	KOE10	JOE10	KOE15	JOE15
Specific gravity at 15 °C	D 4052	0.83	1.15	0.93	0.88	0.935	0.908	0.947	0.9167
Net calorific value (MJ/kg)	D 4809	43.8	20.58	38.41	39.1	30.53	37.24	29.69	36.32
Flash point (°C)	D 93	50	98	204	118	150	160	144	156
Fire point (^{o} C)	D 93	56	108	214	126	-	-	-	-
Pour point (°C)	D 97	-6	2	-3	-1	-	-	-	-
Carbon residue (%)	D 4530	0.1	12.85	0.71	-	-	-	-	-
Kinematic viscosity at 40°C (cSt)	D 445	2.58	25.3	4.3	4.6	7.05	6.91	7.27	7.28
Cetane number	D 613	50	-	57.6	51	-	-	-	-
Moisture content (wt %)	D 2709	0.025	15-30	0.034	-	-	-	-	-
Carbon (%)	D 3178	86.5	49.1	76	77.1	-	-	-	77.2
Hydrogen (%)	D 3178	13.2	6.2	11.6	11.81	-	-	-	12.27
Nitrogen (%)	D 3179	Nil	3.0	0.1	0.119	-	-	-	0.07
Sulphur (%)	D 3177	0.3	0.05	0.002	0.001	-	-	-	0.495
Oxygen by difference (%)	E 385	Nil	41.65	12.29	10.97	-	-	-	9.9

Direct water-oil emulsions show less viscosity than an oil-water emulsion. This property is very important for heavy fuel oil handling. In this investigation, a lipophilic surfactant Span 20 (Sorbitan monolaurate) supplied by Ms.Loba Chemie Private Limited, having hydrophilic-lipophilic balance (HLB) of 8.6 was used to make a water-in-oil emulsion, which will reduce the interfacial tension as well as to improve the adherence between the phases of the WPO and the biodiesel fuels (KME and JME). Four WPO fuel emulsions were prepared from WPO 10% and 15% by volume with KME as well as JME 88% and 83% by volume respectively, with the addition of surfactant Span-20 2% by volume. The resultant mixture was stirred well with a help of mechanical stirrer at 1500rpm for about 30 minutes. Then, the emulsion produced was observed visually for about eight hours, and it was found that the emulsions were stable. There was no phase separation during the observation period. Emulsions prepared with KME and WPO are indicated as KOE10 and KOE15 whereas, emulsions prepared with JME and WPO are denoted as JOE10 and JOE15.

3. EXPERIMENTAL SET-UP

The schematic of the experimental setup is given in Figure 2 and the specification of the test engine was given in Table 4. Experiments were conducted in a single cylinder, four stroke, air cooled, direct injection diesel engine coupled to an alternator. The load act on the alternator was varied with a resistive load bank. The exhaust gas temperature was measured with the help of a K-type thermocouple fitted in the exhaust pipe. Fuel consumption was measured with the help of a solenoid controlled automatic burette. An air box was used to damp out the pulsations produced by the engine, for ensuring a steady flow of air through the intake manifold. Air consumption was measured by an air flow sensor fitted in the air box. A speed sensor was connected near the flywheel of the engine to measure the speed.

Engine exhaust emissions were measured with an AVL 444 exhaust gas analyser that measures unburnt hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2) and nitric oxide (NO) emissions. HC and NO emissions were measured in ppm and CO and CO_2 were measured in percentage volume. An AVL 437C diesel smoke meter was used to measure the smoke opacity of the engine exhaust. Initially, the engine was operated with diesel fuel to get the baseline data, and then with JME. The performance and emission parameters were evaluated. Then, the engine was allowed to run with the emulsions KOE10, KOE15, JOE10 and JOE15. The results were compared with diesel operation. All the experiments were conducted at constant speed of 1500 rpm by keeping the load constant will all the fuels. The engine was allowed to run with diesel fuel in between the WPO emulsions, to eliminate the cumulative effects in the fuel as well as gas analyzer. Finally, the engine was allowed to run with diesel fuel to flush out the WPO emulsions in the fuel line. The engine was able to produce the designed power. Experiments were repeated for about five times to check the consistency of the results.



1. Diesel Tank	2. Emulsion tank	3.Air box	4. Engine
5. Alternator	6. Resistive load	7. Gas Analyzer	8. Smoke meter

Fig. 2. Schematic diagram of experimental set-up.

Table 4. Engine specifications.

Make/Model	Kirloskar TAF 1
Brake power, kW	4.4
Rated speed, rpm	1500
Bore, mm	87.5
Stroke , mm	110
Compression Ratio	17.5:1
Cooling System	Air cooling
Nozzle Opening Pressure, bar	200
Injection Timing, ^{o}CA	23
No. of holes	3

3.1 Error Analysis

Uncertainty is a measure of the 'goodness' of a result. Without such a measure, it is impossible to judge the fitness of the value. Uncertainty or error analysis is necessary to establish the bounds on the accuracy of the estimated parameters. Evaluations of some unknown uncertainties from known physical quantities were obtained using the following general equation [23].

$$\frac{U_Y}{Y} = \left[\sum_{i=1}^{n} \left(\frac{1}{Y} \frac{\partial Y}{\partial xi} U_{xi} \right)^2 \right]^{1/2} \tag{1}$$

In Equation 1, Y is the physical parameter that is dependent on the parameters, xi. The symbol U_Y denotes the uncertainty in Y. As a result, the maximum uncertainty of the experiment obtained was ± 2.07 %. Table 5 shows the instruments used in the present study and their uncertainties.

4. RESULTS AND DISCUSSION

4.1 Performance Parameters

Figure 3 shows the variation of the brake thermal efficiency and specific fuel consumption with brake power for the different fuels tested. Thermal efficiency is the ratio between the power output and the energy introduced through fuel injection, the latter being the product of the injected fuel mass flow rate and the lower heating value (calorific value). Biodiesel emulsions prepared from both karanja and jatropha shows an increasing trend in the brake thermal efficiency compared to that of diesel fuel operation. This may be due to higher viscosities of the emulsified fuel yields to earlier injection compared to that of diesel fuel which in turn increases the delay period. The combustion itself is faster for the emulsions, which explains the increased brake efficiency. Another reason may be the additional oxygen molecule available in the JME that takes part in the combustion and results in complete combustion [24].

Table 5. Accuracy and uncertainty of the instruments.

Instrument		Accuracy	Uncertainty
Load indicator		±10W	0.2
Temperature indicator		±1 ^{o}C	0.1
Burette		±0.2 cc	1.0
Speed sensor		±10rpm	0.1
Exhaust gas analyser –	NO	±50ppm	1
	CO	±10ppm	0.5
	HC	0.03%	1
Smoke meter		±1 %	1

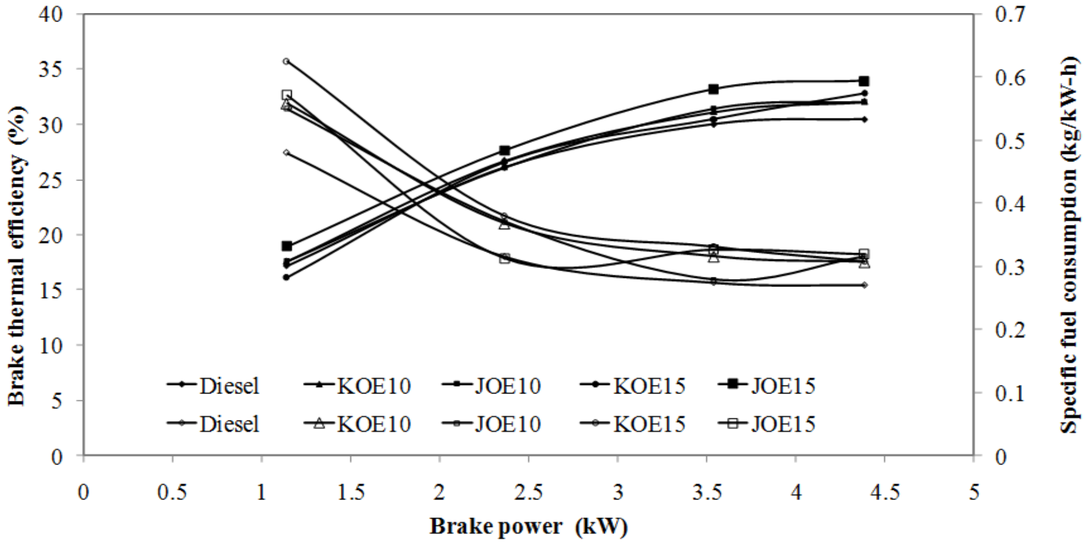


Fig. 3. Variation of the BTE and SFC with brake power.

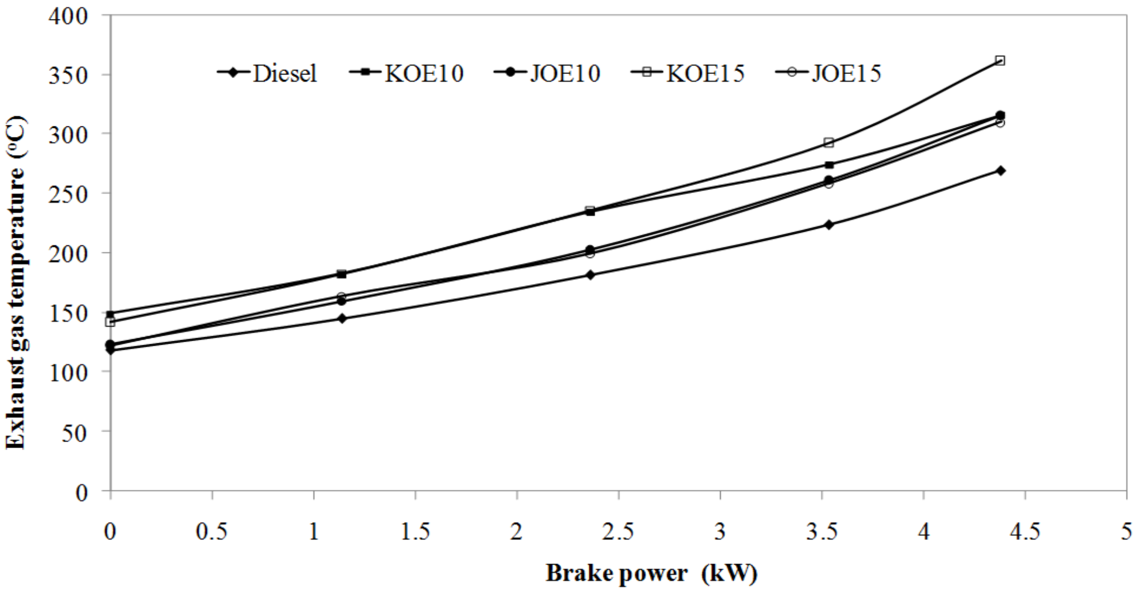


Fig. 4. Variation of the exhaust gas temperature with brake power.

At full load, the emulsions KOE10, JOE10, KOE15 and JOE15 show increased thermal efficiencies in the order of 5%, 4.9%, 7.5% and 11.3%, respectively compared to diesel operation. Out of all, JOE15 operation gives maximum thermal efficiency which is 3.4% higher than that of KOE15 operation. The SFC is minimum in the case of diesel fuel operation which is followed by KOE10, KOE15, JOE10 and JOE15 at the full load condition. The lower calorific value of the biodiesel fuel and its emulsions causes higher specific fuel consumption compared to that of diesel fuel.

Figure 4 shows the exhaust gas temperature variation with respect to brake power. It is observed from the graphs that the emulsions KOE10 and KOE15 show the higher exhaust gas temperature throughout the load spectrum. The heavier molecules of the biodiesel lead to continuous burning, even during the exhaust stroke which causes higher exhaust gas temperature [25].

For JOE10 and JOE15, the exhaust gas temperatures are found to be lower than that of KME emulsions, but higher than that of diesel fuel at full load. Also, it is seen that the exhaust gas temperature of the JME emulsion decreases with an increase in the WPO content. The lower molecular weight components in the emulsion get vaporized during the combustion process, and absorb, the heat energy which decreases the local adiabatic flame temperature [26]. This may result in lower exhaust gas temperature compared to that of biodiesel.

4.2 Emission Parameters

Figure 5 describes the variation of the brake specific hydrocarbon (HC) emissions with respect to brake power. The HC emissions of all biodiesel emulsions are found to be lower than that of diesel. The best improvement in the HC emissions is seen in case of KOE10 and KOE15 followed by JOE10 and JOE15. The reduction in HC is mainly due to the result of improved combustion of biodiesel blends within the combustion period due to the presence of excess oxygen atom in biodiesel [5].

Figure 6 shows the variation of brake specific carbon monoxide (CO) emissions with brake power. Generally, CO emissions are formed as a result of incomplete combustion of fuel. However, if the combustion is complete, CO will be oxidized into CO_2 [27].

For JOE10 and KOE10 emulsions, the CO emissions are found to be lower by 25% than that of diesel fuel at all load and about 50% lower CO emissions were noticed with JOE15 and KOE15 emulsions.

Figure 7 depicts the variation of the brake specific nitric oxide (NO) emissions with respect to brake power. The NO emissions decrease with the increase in the engine load. More fuel is burned inside the engine during high loads, which results in high temperature. This will facilitate the oxidization of nitrogen, which in turn, results in higher NO emissions according to the extended Zeldovich thermal NO mechanism [28]. It is observed that about 0.5%, 3.1% and 2.2% increase in the NO emissions are obtained with KOE15, JOE10 and KOE10 respectively, at full load compared to that of diesel.

The presence of oxygen molecule in biodiesel causes an increase in combustion gas temperature resulting in a marginal increase in NO emissions [29]. At elevated flame temperature, this oxygen reacts with nitrogen and tends to form NO. There is a decrease in the NO emissions by 3% when fueled with JOE15 at full load. Also the NO emissions decrease with addition of WPO in all the emulsions and this may be due to more water content in WPO reduces the combustion temperature [19].

Figure 8 describes the variation of the smoke opacity with respect to brake power. Smoke opacity of all the biodiesel emulsions with WPO is lower than diesel fuel.

This reduction in smoke opacity in case of all the biodiesel test fuels is due to the absence of sulphur, aromatic and presence of oxygen which plays a vital role for complete combustion of fuel. The percentage decrease in the smoke opacity of 16.4 %, 18.5%, 13.5% and 18.2% was obtained for KOE10, JOE10, KOE15 and JOE15 respectively at full load, when compared with diesel. This may be due to the effects of enhancement in the spray volume, considerable amount of air entrainment in the emulsion spray, and the micro-explosion effect during the combustion process [30].

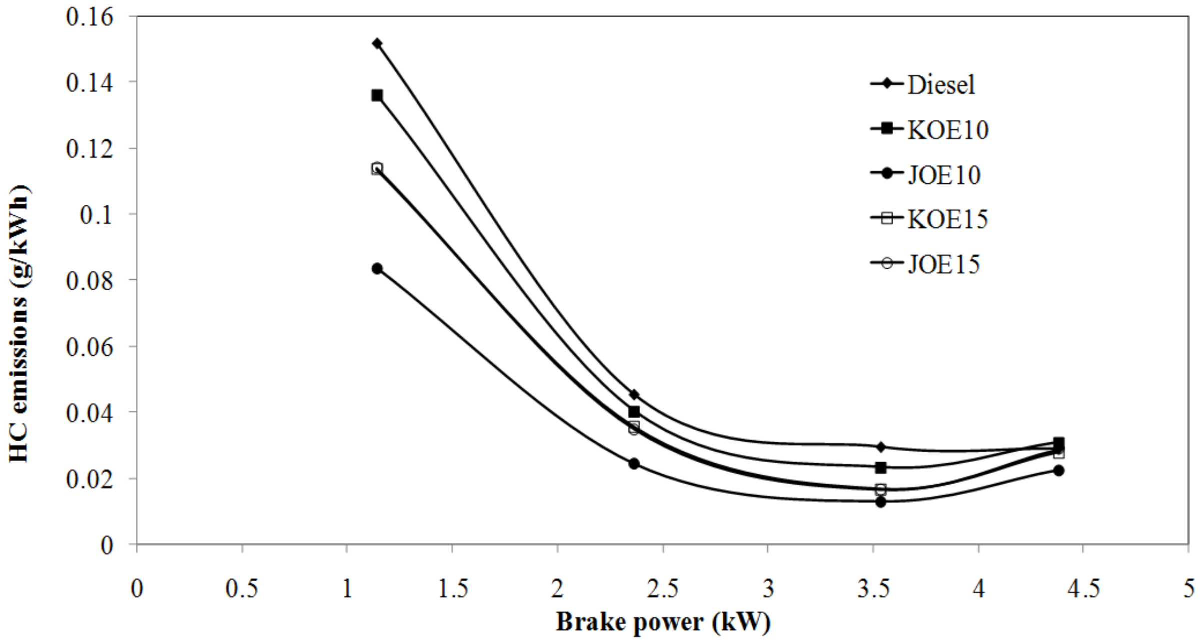


Fig. 5. Variation of the BSHC emissions with brake power.

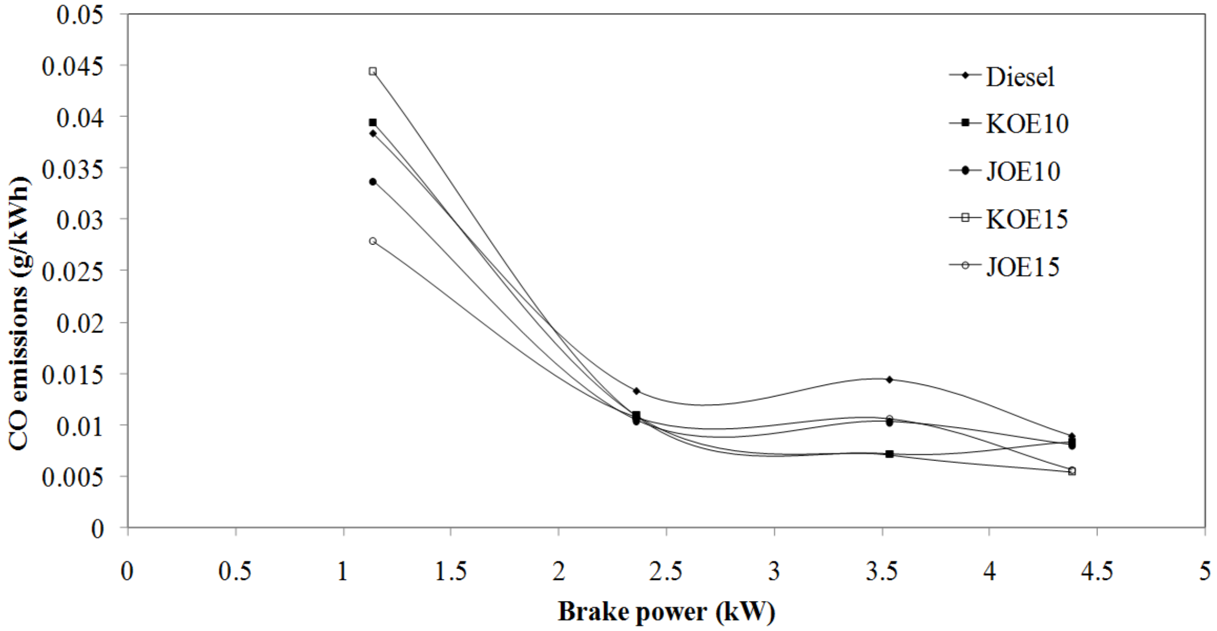


Fig. 6. Variation of the BSCO emissions with brake power.

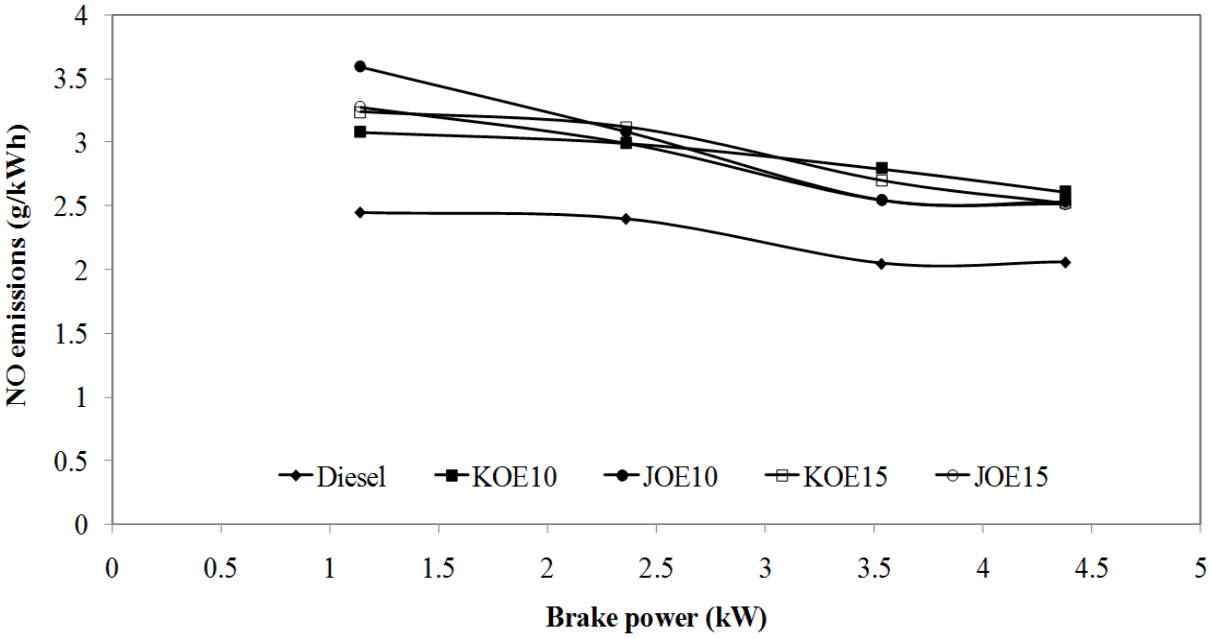


Fig. 7. Variation of the BSNO emissions with brake power.

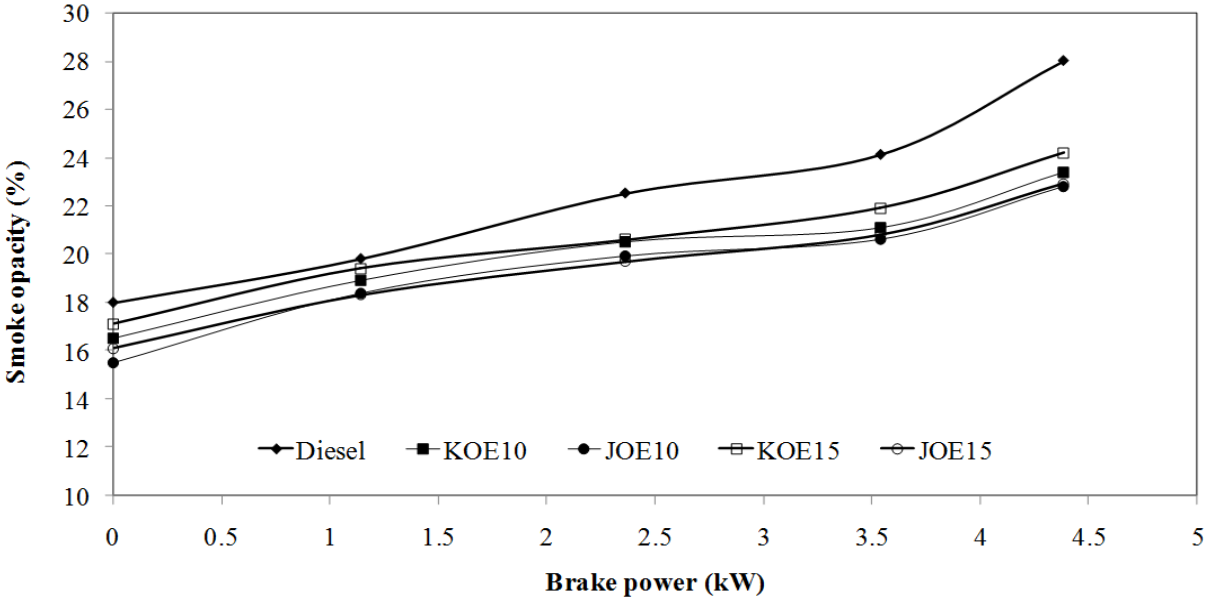


Fig. 8. Variation of the smoke opacity with brake power.

5. CONCLUSIONS

The comparative study of the performance and emission characteristics of a single cylinder, 4-stroke, air-cooled, direct injection diesel engine fueled with two different emulsions were investigated and following conclusions are drawn from the analysis:

1. At full load, the emulsions KOE10, JOE10, KOE15 and JOE15 show increased thermal efficiencies in the order of 5%, 4.9%, 7.5% and 11.3%, respectively compared to that of diesel operation.
2. The SFC is minimum in the case of diesel fuel operation which is followed by KOE10, KOE15, JOE10 and JOE15 at the full load condition.
3. For JOE10 and JOE15, the exhaust gas temperatures are found to be lower than that of KME emulsions, but higher than that of diesel fuel at full load. Also, the exhaust gas temperature of the JME emulsion decreases with an increase in the WPO content.
4. The HC emissions of all biodiesel emulsions are found to be lower than that of diesel. The best improvement in the HC emissions is seen in case of KOE10 and KOE15 followed by JOE10 and JOE15.
5. For JOE10 and KOE10 emulsions, the CO emissions are found to be lower by 25% than that of diesel fuel at all load and about 50% lower CO emissions were noticed with JOE15 and KOE15 emulsions.
6. It is observed that about 0.5%, 3.1% and 2.2% increase in the NO emissions are obtained with KOE15, JOE10 and KOE10 respectively, at full load compared to that of diesel. There is a decrease in the NO emissions by 3% when fueled with JOE15.
7. The percentage decrease in the smoke opacity of 16.4 %, 18.5%, 13.5% and 18.2% is obtained for KOE10, JOE10, KOE15 and JOE15 respectively, at full load in comparison with diesel**.**

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ACRONYMS AND ABBREVIATIONS

WPO	Wood Pyrolysis Oil
KME	Karanja Methyl Ester
JME	Jatropha Methyl Ester
KOE	Karanja Oil Emulsion
JOE	Jatropha Oil Emulsion
HC	Hydrocarbons
CO	Carbon monoxide
NO	Nitric Oxide
GC-MS	Gas Chromatography Mass Spectroscopy
NaOH	Sodium Hydroxide
HLB	Hydophilic Lipophilic Balance

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