An Experimental Investigation of Petrodiesel and Cotton Seed Biodiesel (CSOME) in Diesel Engine

P. V. Rao, Jaedaa Abdulhamid

Abstract**—**Biodiesel is widely investigated to solve the twin problem of depletion of fossil fuel and environmental degradation. The main objective of the present work is to compare performance, emissions, and combustion characteristics of biodiesel derived from cotton seed oil in a diesel engine with the baseline results of petrodiesel fuel. Tests have been conducted on a single cylinder, four stroke CIDI diesel engine with a speed of 1500 rpm and a fixed compression ratio of 17.5 at different load conditions. The performance parameters evaluated include brake thermal efficiency, brake specific fuel consumption, brake power, indicated mean effective pressure, mechanical efficiency, and exhaust gas temperature. Regarding combustion study, cylinder pressure, rate of pressure rise, net heat release rate, cumulative heat release, mean gas temperature, mass fraction burned, and fuel line pressure were evaluated. The emission parameters such as carbon monoxide, carbon dioxide, un-burnt hydrocarbon, oxides of nitrogen, and smoke opacity were also measured by a smoke meter and an exhaust gas analyzer and compared with baseline results. The brake thermal efficiency of cotton seed oil methyl ester (CSOME) was lower than that of petrodiesel and brake specific fuel consumption was found to be higher. However, biodiesel resulted in the reduction of carbon dioxide, un-burnt hydrocarbon, and smoke opacity at the expense of nitrogen oxides. Carbon monoxide emissions for biodiesel was higher at maximum output power. It has been found that the combustion characteristics of cotton seed oil methyl ester closely followed those of standard petrodiesel. The experimental results suggested that biodiesel derived from cotton seed oil could be used as a good substitute to petrodiesel fuel in a conventional diesel without any modification.

Keywords**—**Diesel engine, Cotton seed, Biodiesel, performance, combustion, emissions.

I. Introduction

THE concept of using vegetable oil as an engine fuel is likely surprisingly old. It dates back when Dr. Rudolf Diesel (1858-1913) developed the first engine to run on peanut oil. After his death and due to the rapid developing of petroleum industry and the widespread availability and low cost of petrodiesel fuel, vegetable oil-based fuels gained little attention except in times of high oil prices and shortages. World War II and the oil crises of the 1970's saw brief interest in using vegetable oils to fuel diesel engines [1]. Today people are rediscovering the environmental and economic benefits of making fuel from raw and used vegetable oils.

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Biodiesel is renewable, biodegradable alternative fuel of petrodiesel. It is ready available, clean burning, 100% natural energy source and environmentally friendly [2]. Since it has higher flash point than petrodiesel, it is safer for use, storage and transportation [3]. It has higher combustion efficiency because of the presence of excess amount of oxygen. However, it combusts earlier and has shorter ID period since it has higher cetane number [4]. It acts as a solvent because of its improved lubricity which helps loosen deposits from the insides of an engine. Therefore, it reduces engine wear resulting in increasing of engine life [5]. Biodiesel doesn't contribute to acid rain formation since they have negligible sulfur content [6]. Cotton seed oil is a vegetable oil extracted from the seeds of the cotton plant after the cotton lint has been removed. Cotton seed oil biodiesel will be tested in this work because it is an important product in Syria.

II. Experimental Set-Up

The experimental tests were conducted on a single-cylinder, four-stroke, and water cooled diesel engine with eddy current dynamometer having a rated output of 3.5 kW at a constant speed 1500 rpm. It was fuelled with CSOME and PD fuel separately and was operated at different engine load conditions. The chosen plant oil properties which are for cotton seed oil are given in Table I. The technical specifications of the engine are given in Table II. The Eddy current dynamometer was coupled to the engine for different loading (0-12 kg) conditions. The engine and dynamometer were interfaced to a control panel which is connected to a computer. The exhaust gas emissions from the engine was measured using AVL multi exhaust gas analyzer (NO_x, HC, CO, CO_2, O_2) and the smoke opacity was measured using AVL smoke meter. AVL angle encoder provided at the extended shaft of the dynamometer was used to measure the pressure and crank angle of the engine. Piezoelectric transducer fitted on the cylinder head to measure pressure in the combustion chamber was connected to a console which in turn was connected to the computer. This computerized test rig was used for calculating the engine combustion and performance characteristics like brake thermal efficiency and specific fuel consumption and for recording the test parameters like fuel flow rate, temperatures, air flow rate, and load etc. **IC Engine Soft ver.9.0.** software was used to generate reports of values related to combustion and performance analysis at different loads. Table III gives a comparison between petrodiesel and biodiesel properties.

TABLE I
COTTON SEED OIL PROPERTIES

Properties	Element	Value
Carbon chain C_n	-	C_{14}-C_{22}
MW (g/mol)	-	859.64
Fatty acids (%)	Saturated	27
	Unsaturated	73
	Mono-unsat	20
	Poly-unsat	53
	Unsat-sat	2.7
Iodine value (g I_2/100g)	-	98-115
Cetane number	-	41.8
kV @40°C (mm^2/s)	-	34
Density @15°C (kg/ m^3)	-	915
Composition (%)	C	70.96
	H	11.43
	N	1.31
	O	9.46
	S	0.29
	C/H	6.2
A/F Ratio (Stoicho)	-	12.4
LCV (MJ/ kg)	-	40.38

TABLE II
TECHNICAL SPECIFICATIONS OF ENGINE TEST RIG

Model	Kirloskar TV1 engine
Engine type	Four stroke diesel engine
Number of cylinders	One
Cooling system	Water
Rated power	3.5 kW
Bore × Stroke	87.50× 110.0 (mm×mm)
Connecting Rod length	234 mm
Compression ratio (variable)	17.5:1
Fuel injection system	In-line, direct injection
Fuel injection timing	23° BTDC
IVO	4.5° BTDC
IVC	35.5° ABDC
EVO	35.5° BBDC
EVC	4.5° ATDC
Nozzle opening pressure	215 kgf/cm^2
Rated speed (constant speed)	1500 rpm
Swept volume	661.45 (cc)
Loading device	Eddy current dynamometer (water cooled)
Dynamometer Arm Length	185 mm

III. RESULTS AND DISCUSSIONS

A four stroke water cooled single cylinder direct injection diesel engine was run successfully using cotton seed biodiesel and petrodiesel fuel. The combustion, performance and emission characteristics of the engine were analyzed and compared to baseline results.

A. Combustion Analysis

It is observed in Fig. 1 that biodiesel has higher cylinder pressure (CP) than petrodiesel because of earlier ignition and higher peak pressure attributed to the advanced injection due to higher density (bulk modulus) of biodiesel. When biodiesel is injected, the pressure wave travels faster from pump end to nozzle end through a high pressure in-line tube. This causes an early lift of needle in the nozzle causing advanced injection, hence the combustion takes place very close to TDC and peak pressure increases due to existence of smaller cylinder volume [7]. Fig. 2 represents the variation in net heat release rate (NHRR) with change in crank angle at maximum output power. It is observed that the amount of heat release during premixed combustion is higher for biodiesel than that of petrodiesel attributed to the combined effect of advanced injection and lower value of heat rejection due to prevalence of smaller cylinder volume (surface area) near TDC [8].

The amount of heat release during diffusion phase is observed to be lower for biodiesel because of poor mixing of biodiesel with surrounding air due to higher viscosity and slower evaporation. Therefore, less burning occurs in the diffusion phase rather than premixed phase. The total amount of heat released during premixed and diffusive phase is called cumulative heat release (CHR) which is represented in Fig. 3 and observed to be higher for petrodiesel comparing to biodiesel. Another measured combustion parameter is mean gas temperature (MGT) shown in Fig. 4 which represents its variation with crank angle change. It is observed that mean gas temperature is lower for biodiesel because of its lower calorific value. Fig. 5 shows the variation in mass fraction burned with change in crank angle at maximum output power. More mass fraction burned was observed for biodiesel due to the excess of extra oxygen which leads to more effective combustion. The less unsaturated biodiesel could find more oxygen than that of a more unsaturated biodiesel.

Fig. 6 shows that biodiesel has higher fuel line pressure (FLP) with early injection due to its higher density comparing to petrodiesel. Rate of pressure rise values (RPR) of biodiesel are higher comparing to those of petrodiesel due to its higher cetane number which results in early injection near TDC as it is observed in Fig. 7. It is observed that ignition delay decreases with load increasing because of more engine operating temperature which leads to faster fuel burning and shorter ignition delay as a result.

B. Performance Analysis

Fig. 8 shows an increase in mechanical efficiency values for petrodiesel and biodiesel with brake power increase. For biodiesel, mechanical efficiency is lower than that of petrodiesel at each brake power corresponding value due to lower volatility and higher density of esters which affect the atomization of the fuel leading to poor combustion [9]. It is noticed in Fig. 9 that brake thermal efficiency is less in case of using biodiesel instead of petrodiesel at each brake power corresponding value due to lower calorific value as it has higher oxygen content and due to higher viscosity of biodiesel which results in slower combustion, hence reducing brake thermal efficiency.

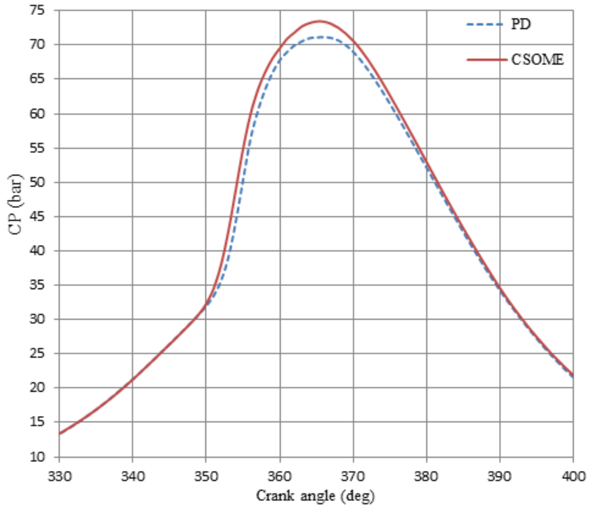

Fig. 1 Variation in cylinder pressure with change in crank angle at maximum output power

TABLE III
PETRODIESEL AND BIODIESEL (CSOME) PROPERTIES

Properties	PD	CSOME (B100)
Fuel Density@15°C (kg/m³)	830	882
Kinematic viscosity@40°C (mm²/s) or (cSt)	2.58	4.1
Cetane Number	48	54
Low heating value (MJ/kg)	42.50	39.40
Flash point (°C)	50	178
Fire point (°C)	56	183
Calorific value (kJ/kg)	42500	39500
Carbon content (C)	86.25	76.8
Hydrogen content (H)	12.5	12
Sulfur (S)	0.25	negligible
Oxygen content (O_2) (%)	0	11
C/H ratio	6.9	6.4

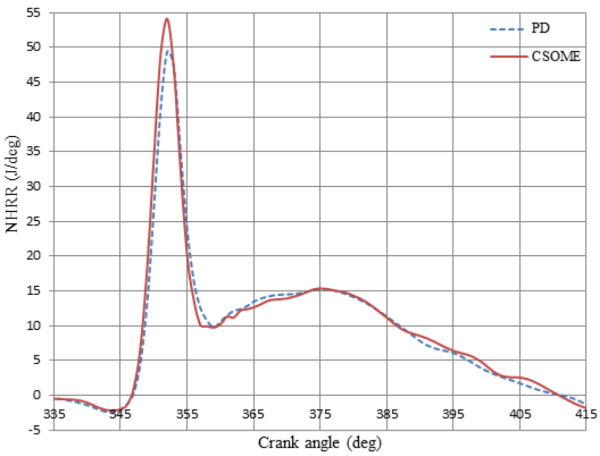

Fig. 2 Variation in net heat release rate with change in crank angle at maximum output power

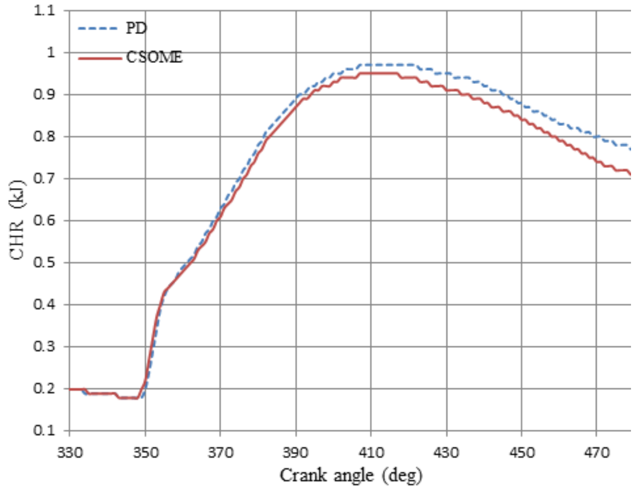

Fig. 3 Variation in cumulative heat release with change in crank angle at maximum output power

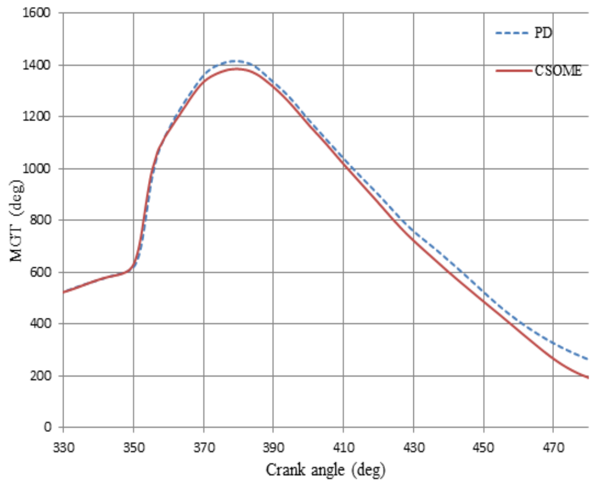

Fig. 4 Variation in mean gas temperature with change in crank angle at maximum output power

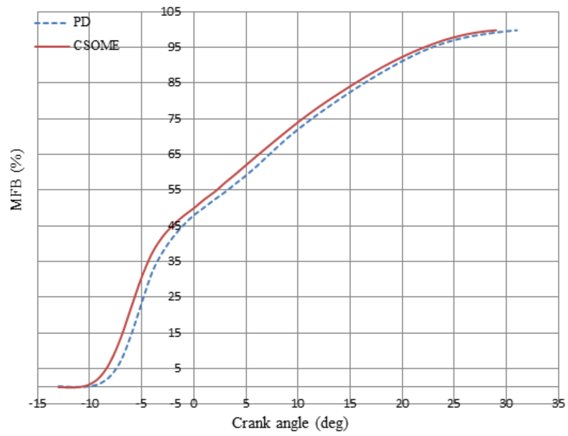

Fig. 5 Variation in mass fraction burned with change in crank angle at maximum output power

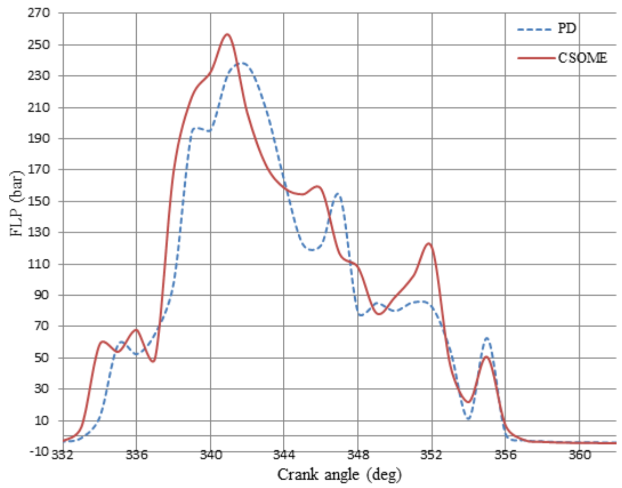

Fig. 6 Variation in fuel line pressure with change in crank angle at maximum output power

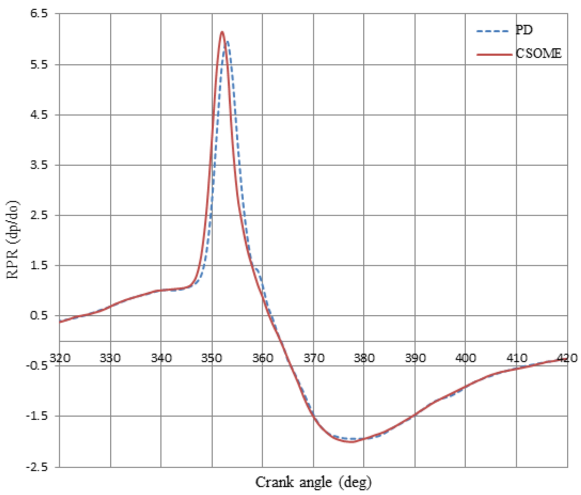

Fig. 7 Variation in rate of pressure rise with change in crank angle at maximum output power

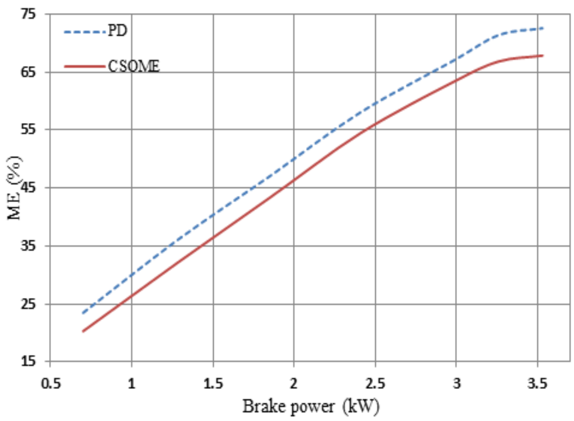

Fig. 8 Variation in mechanical efficiency with change in brake power

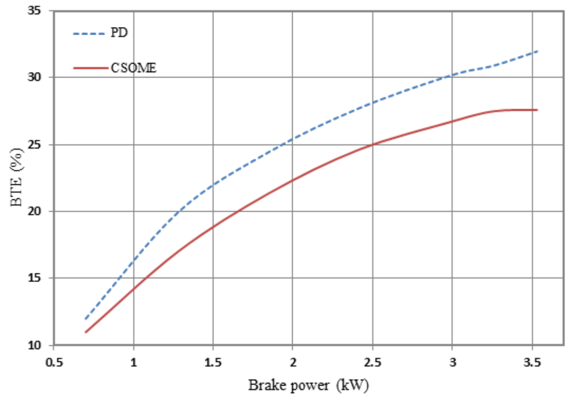

Fig. 9 Variation in brake thermal efficiency with change in brake power

Fig. 10 indicates an increase in the exhaust gas temperature of the petrodiesel fuel over the biodiesel at low and high load levels which may be attributed to the increased cylinder pressure due to improved combustion of fuel as a result of improved atomization at warmed-up condition. Fig. 11 represents Variation in indicated mean effective pressure with change in brake power which is observed to be higher for biodiesel due to the same previously mentioned reasons regarding early injection of biodiesel near TDC. It is well known that brake specific fuel consumption is inversely proportional to the brake thermal efficiency. Therefore, petrodiesel has higher brake specific fuel consumption as it is observed in Fig. 12.

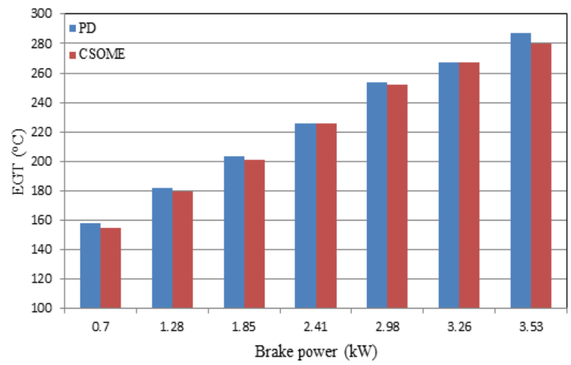

Fig. 10 Variation in exhaust gas temperature with change in brake power

C. Gas Emissions Analysis

Carbon monoxide emission concentrations in the exhaust gases are a measure of the combustion efficiency of the system. At low loads, combustion is more complete and CO emissions are much lower.

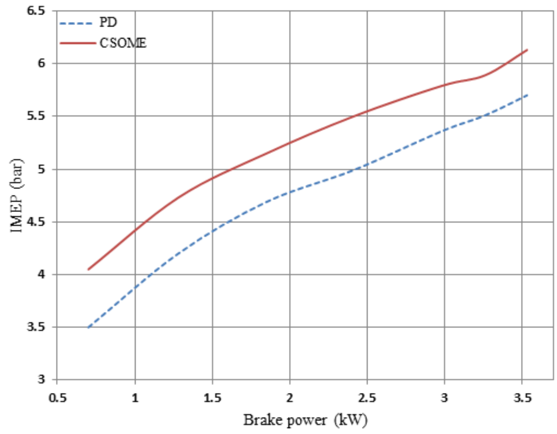

Fig. 11 Variation in indicated mean effective pressure with change in brake power

The biodiesel showed a decrease in CO emissions at low load levels as it is shown in Fig. 13. However, the increasing trends of carbon monoxide emission levels are observed with power output at high loads for both fuels due to higher peak pressures (and also higher rate of pressure rise with is more than 6) which leads to higher knock levels and less smooth combustion leading to increase of CO at high load levels [10].

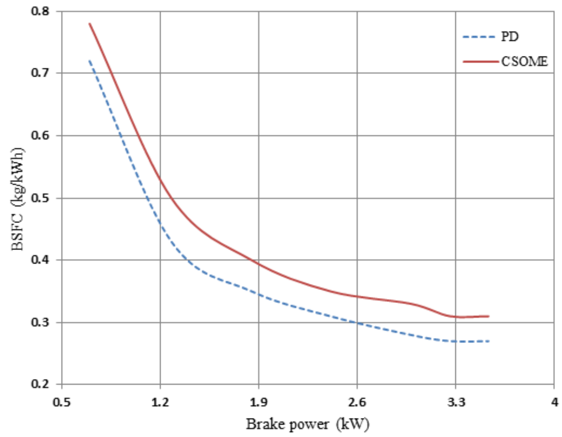

Fig. 12 Variation in brake specific fuel consumption with change in brake power

Biodiesel results in better combustion rate as it contains 11% oxygen content and has higher cetane number which leads to burn the fuel completely during combustion thereby the formation of HC emission become lower as it is observed in Fig. 14. As petrodiesel fuel viscosity decreases, the spray cone angle increases and the penetration length decreases, hence HC emissions are noted to increase. The lower vapor pressure of biodiesel means fewer evaporative losses and lower unburned hydrocarbon emissions.

The reason for higher level of HC at 0 kW power output is attributed to the flame quenching and cooled layer of the charge near the cylinder walls during the cold start [11]. It is less than petrodiesel due to inherent presence of oxygen in the molecular structure of biodiesel.

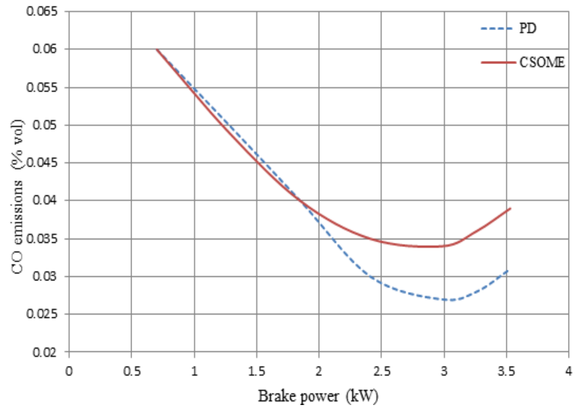

Fig. 13 Variation in CO emission with change in brake power

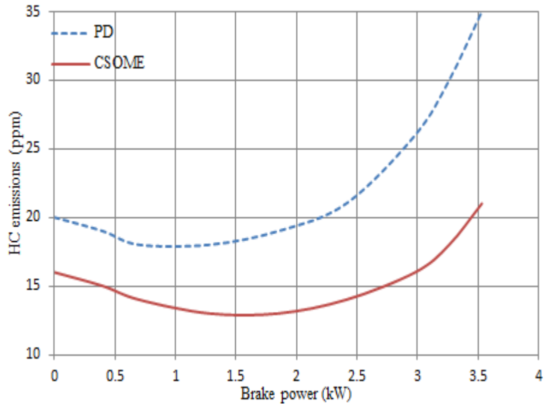

Fig. 14 Variation in HC emission with change in brake power

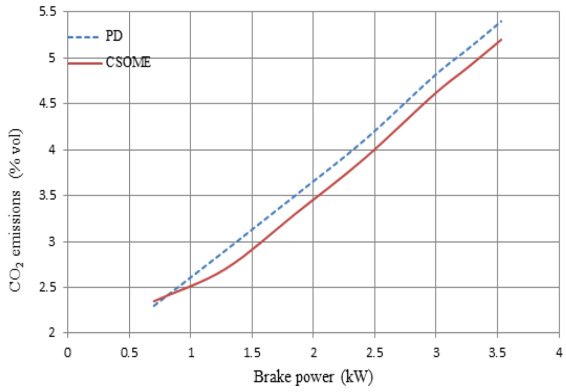

Fig. 15 Variation in CO_2 emission with change in brake power

Fig. 15 represents variation in CO_2 emission with change in brake power which is observed to be lower for biodiesel because as the viscosity increases, the cone angle decreases and penetration length increases which results in reduction of the amount of air entrainment in the spray hence the emissions of CO_2 were noted to decrease.

At small loads, very little fuel is injected resulting in very low NO_x levels, thus NO_x emissions are roughly proportional to the mass of fuel injected. NO_x emissions tend to be higher at higher loads with higher peak pressures and higher temperatures because of high duration of combustion attributed to high cetane number associated with the availability of oxygen which drastically cause higher NO_x levels. It is shown in Fig. 16 that biodiesel and petrodiesel have similar NO_x emission trends but biodiesel seems to have slightly higher NO_x emissions than petrodiesel. The increased engine loads promote NO_x emissions. Since the formation of NO_x is very sensitive to temperature which is responsible for thermal (Zeldovich) NO_x formation. Also long chain biodiesel produces more NO_x than petrodiesel. Also the higher bulk modulus (density) leads to early injection which contributes towards large premixed combustion which is responsible for thermal NO_x production. Higher levels of oxygen lead to improvement in oxidation of the nitrogen available during combustion which will raise the combustion bulk temperature responsible for thermal NO_x formation. It is also observed that the higher the peak pressure of premixed combustion, the larger will be the NO_x formation [12]. Fig. 17 shows that smoke opacity increases with load increment for biodiesel and petrodiesel. During the first part, smoke level is almost constant due to excess air presence. However, at higher load range, there is an abrupt rise in smoke levels due to more fuel to air ratio, hence incomplete combustion and more soot density [13].

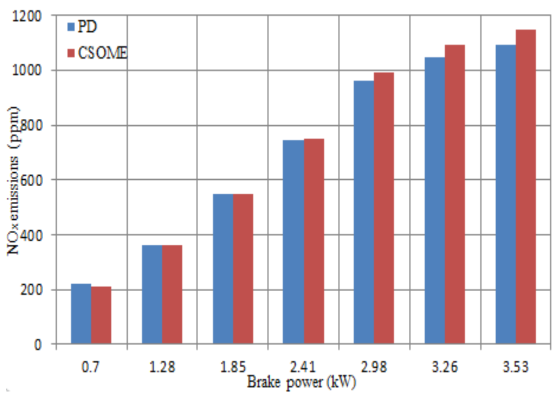

Fig. 16 Variation in NO_x emission with change in brake power

Cetane number is an indicator for the fuel in terms of quality, hence the higher the cetane number, the better the ignition property of the fuel by producing less black smoke [14]. It is observed that as the ratio of carbon to hydrogen increases, the fuel tendency of smoke emission producing increase.

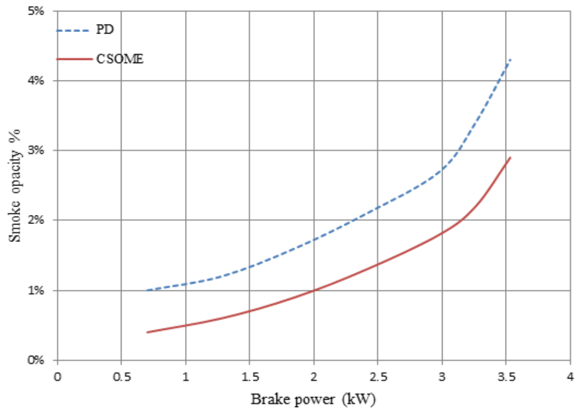

Fig. 17 Variation in smoke opacity with change in brake power

IV. Conclusions

Based on the experimental study, the following conclusions are summarized as follows:

Due to the higher density of biodiesel, an early injection occurs resulting in higher cylinder pressure which is about (3.19%) at maximum output power. Same reasons lead to higher premixed combustion for biodiesel for about (9.6%), but for diffusive combustion is less due to higher viscosity and lower volatility of biodiesel. Biodiesel has higher mass fraction burnt comparing to petrodiesel (0.01%) at maximum output power due to its more effective combustion as it has extra amount of oxygen. There is a decrease in brake thermal efficiency of CSOME comparing to PD (11.58%) since it has lower calorific value due to the presence of excess oxygen. Mechanical efficiency is slightly lower for CSOME (8.12%) due to its higher viscosity and lower volatility. Indicated mean effective pressure of CSOME is 10.12% higher than that of PD. Brake specific fuel consumption of CSOME is 14.18% higher than that of PD due to its lower energy content. A drastic reduction in unburned hydrocarbon (37.9%) and smoke opacity (32.56%) were recorded for CSOME as compared to PD because of its higher oxygen content which results in better and complete combustion but this leads also to an increase in oxides of nitrogen. As the carbon to hydrogen ration reduces, the biodiesel tends to produce less smoke opacity. Regarding carbon monoxide, there is an increase for CSOME compared to PD at maximum output power due to higher peak pressures (and also higher rate of pressure rise which is more than 6) leading to higher knock levels and less smooth combustion. In case of carbon dioxide, there is a 3.7% decrease for CSOME compared to PD because of its higher viscosity which leads to decrease the cone angle and results in the reduction of air entrainment in the spray.

In the case of oxides of nitrogen, there is a 5.023% increase for CSOME compared to PD due to higher oxygen content of biodiesel which will form oxides of nitrogen at high combustion temperatures.

On the whole, the methyl esters of cottonseed oil can be used as an alternative fuel for (CIDI) diesel engines without any engine modification. It gives lower un-burnt hydrocarbon,

carbon dioxide and smoke emissions when comparing to petrodiesel fuel at the expense of nitrogen oxides and carbon monoxide emissions.

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