ISSN 2229-5518

Experimental Investigation on the Effect of Biodiesel derived from Cottonseed oil (Gossypium hirsutum) on Environmental Emissions and Performance of a Stationary DI Diesel Engine

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Abstract – Biodiesel fuels are becoming increasingly popular because of their lowest impact on environment and better potential as a green alternative fuel as well as renewable fuel source for diesel engines. The carbon monoxide, hydrocarbons, and particulate matter emissions are lower with biodiesel as compared to diesel fuel. Due to inherent oxygen content and various fuel characteristics, biodiesel exhibits higher oxides of nitrogen emissions when compared to petro-diesel. Similarly, engines fueled with biodiesels show closer performance characteristics to that of diesel fuel. In the present work, experiments were conducted in a constant speed, stationary direct injection diesel engine fueled with diesel, cottonseed oil, and cottonseed biodiesel to investigate the performance and emission characteristics. The tests conducted with standard injection pressure and timing at different engine loads, i.e. 25%, 50%, 75%, and 100% of the rated load. The performance of the engine was evaluated by brake specific fuel consumption, brake thermal efficiency, and exhaust gas temperature. Correspondingly, emissions were evaluated in terms of the oxides of nitrogen and smoke emissions. It was found from the investigation that the cotton biodiesel showed performance and emissions closer to petroleum diesel fuel.

Index Terms— Biodiesel, Cottonseed, Diesel engine, Environmental emissions, Performance

1 Introduction

A number of research and development efforts on internal-combustion engines have taken place in finding suitable alternatives for diesel fuel due to its increasing exhaustion and demand across globe. In this context biodiesel fuels, which can be produced by transesterification of the plant oils with methanol are becoming more popular because of their eco-friendly nature [1]. Researches on the performance of biodiesel fuels in unmodified diesel engines reveal that they are excellent choices for diesel fuels among the many different types of substitute fuels [2-8]. Biodiesel has about 10% oxygen content (by weight) and has no aromatics. Compared with diesel fuel, biodiesel reduce the emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) in the exhaust gas [9]. However, because of combustion and some fuel characteristics, oxides of nitrogen (NO_X) emissions of biodiesel increase. Edible oils such as soybean, sunflower, saffola etc. are used for production of biodiesel in most of the American and European countries. India is still a net-importer of edible vegetable oils and hence biofuels research cannot be based on edible vegetable oils. In India, for production of biodiesel and utilization in diesel engines variety of non-edible oils like linseed, mahua, karanja, rice bran, jatropha, rubber seed, and cottonseed are available in abundance which can be utilized [10-12]. Not much works are available on the use of Cottonseed oil on diesel engine. Different physical and chemical structures exist in spite of part similarities among vegetable oils and diesel fuel. Uses of straight vegetable oils in diesel engines create problems, due to the high viscosity and lower volatility of vegetable oils [13]. Modifications are to be made in vegetable oils to bring their combustion related properties closer to diesel. This main aim of fuel modification is reducing the viscosity to eliminate the problems related to flow/atomization. Four techniques can be implemented to reduce the viscosity of vegetable oils; namely dilution/blending, heating/pyrolysis, transesterification, and micro-emulsion [13, 14]. The extent of performance alteration will depend on the fuel used and on the engine compassion to fuel injection and combustion characteristics [15-17]. Transesterification is well-known and best suitable method of using vegetable oils in diesel engine without significant long-term durability issues. In the present study, the environmental emissions and performance parameters of a stationary agricultural type diesel engine fueled with biodiesel derived from cottonseed oil are investigated experimentally.

2 Experiments

2.1 Fuel Preparation and Properties

The cottonseed biodiesel was produced in the authors' laboratory through transesterification. A process of producing a reaction in triglyceride and alcohol in the presence of a catalyst to produce alkyl ester and glycerol is called as transesterification. To catalyze the reaction, alkali's (Sodium hydroxide, potassium hydroxide) and acids (Sulphuric acid Hydrochloric acid) are used [18-20]. Alkali catalyzed transesterification is faster than acid catalyzed transesterification and is ideal commercially [21]. Good quality of biodiesel can be produced, if the free fatty acid (FFA) content and moisture content are less than 0.5%. The objective of the transesterification process is to reduce the

ISSN 2229-5518

viscosity of vegetable oil. In the present work, single stage transesterification process was followed. The fuel properties were determined following the methods specified in ASTM standards and the fatty acid profile was determined using gas chromatography. The properties of diesel, cotton seed oil, and cottonseed biodiesel are given in Table 1. The fatty acid composition of cottonseed biodiesel is given in Table 2.

Table 1: Properties of Test Fuels

Property	Unit	Diesel	Cotton seed oil	Cotton seed biodiesel
Specific gravity	kg/m³	0.830	0.992	0.886
Kinematic viscosity (at 40°C)	mm²/s	3.40	33.51	4.53
Cetane number	-	48	38	52
Heating Value	MJ/kg	42	35	38
Flash point	°C	50	192	162

Table 2: Fatty Acid Composition of Cottonseed Biodiesel

Fatty acid name	C:N	Chemical formulae	Type	Wt (%)
Lauric	C12:0	$C_{12}H_{24}O_2$	Saturated	0.10
Myristic	C14:0	$C_{14}H_{28}O_2$	Saturated	1.0
Palmitic	C16:0	$C_{16}H_{32}O_2$	Saturated	20.1
Stearic	C18:0	$C_{18}H_{36}O_2$	Saturated	2.6
Oleic	C18:1	$C_{18}H_{34}O_2$	Unsaturated	19.2
Linoleic	C18:2	$C_{18}H_{32}O_2$	Unsaturated	56.4
Linolenic	C18:3	$C_{18}H3_2O_2$	Unsaturated	0.6

In C: N, C indicates the number of carbon atoms and N the number of double bonds of carbon atoms in the fatty acid chain

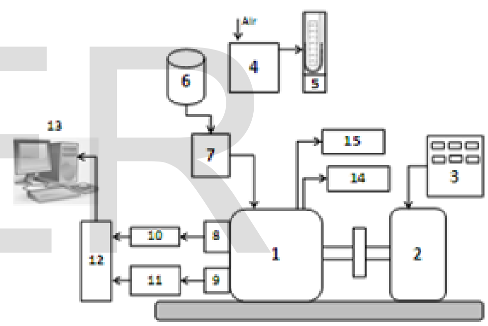
2.2. Experimental Set-up and Test Procedure

Experiments were carried out in a Kirloskar TAF-1 single cylinder, four-stroke, air cooled, direct injection, compression ignition engine, 4.4 kW with a constant speed of 1500 rpm and the specifications are given in Table 3. A swinging field electrical dynamometer was used to apply the load on the engine. This electrical dynamometer consists of a 5 kVA AC alternator (220V, 1500 rpm) mounted on bearings and on a rigid frame for the swinging field type of loading. The output power was obtained by accurately measuring the reaction torque by a strain gauge type load cell. A water rheostat with an adjustable depth of immersion electrode was provided to dissipate the power generated. By switching on the load mains of the electrical dynamometer; the engine was gradually loaded to full-load. The recommended injector opening pressure by the manufacturer was 200 bar. The consumption time for 10cc of fuel was measured using a stopwatch. To eliminate the uncertainty, the tests were repeated for five times and the average value of the five readings was taken.

The exhaust gas temperature and emissions such as oxides of nitrogen (NOX) and smoke were measured at different loads. Oxides of nitrogen emission were measured with MRU 1600 exhaust gas analyzer and the smoke intensity was measured with Bosch smoke meter. A thermocouple is fitted to the exhaust pipe to measure the exhaust gas temperature. The schematic of the experimental setup is shown in fig. 1. To begin with the engine was started and allowed to stabilize for 45 minutes. The engine was fueled with neat diesel, cotton seed oil, and its biodiesel respectively. The performance and emission parameters were measured at different loads.

Table 3: Test Engine Specification

Parameters	Specification
Make	Kirloskar
Model	TAF 1
Bore x Stroke (mm)	87.5 x 110
Compression ratio	17.5 : 1
Engine capacity	0.661 litres
Rated power	4.4 kW
Rated speed	1500 rpm
Start of Injection (SOI)	23.4°bTDC



1. Diesel engine	6. Fuel tank	11. TDC amplifier circuit
2. Electrical dynamometer	7. Fuel measurement	12. A/D card
3.Dynamometer controls	8. Pressure transducer	13. Personal computer
4. Air tank	9. TDC position sensor	14. Exhaust gas analyzer
5. U-tube manometer	10. Charge amplifier	15. Smoke measurement

Fig. 1. Experimental set-up schematic

2.3 Error Analysis

The errors involved with various measurements and in calculations of performance parameters are computed in this section using the method proposed by JP Holman [22]. The uncertainty in computed result of measured variables is given as,

$$\Delta R=\left[\left(\frac{\partial R}{\partial x_1}\Delta x_1\right)^2+\left(\frac{\partial R}{\partial x_2}\Delta x_2\right)^2+.....+\left(\frac{\partial R}{\partial x_n}\Delta x_n\right)^2\right] \quad (1)$$

Where, R is the computed result of the measured variables x_1, x_2, x_n (i.e. R is a function of x_1, x_2, and x_n), Δx_1, Δx_2, Δx_n are the uncertainties in the independent measured variables and ΔR = uncertainty of the computed result.

Uncertainty in brake power, total fuel consumption, and brake thermal efficiency are calculated using equations (2), (3), and (4), respectively. The uncertainty in brake power is,

$$\Delta(\text{Brake Power})=\left[\sqrt{\left(\frac{\partial(BrakePower)}{\partial V}x\Delta V\right)^2+\left(\frac{\partial(BrakePower)}{\partial I}x\Delta I\right)^2}\right] \quad (2)$$

Where, ΔV and ΔI are the uncertainties in voltage and current. The uncertainty involved in total fuel consumption (TFC) is,

$$\Delta(\text{TFC})=\sqrt{\left(\frac{\partial(\text{TFC})}{\partial t}x\,(\Delta t)\right)^2} \quad (3)$$

Where, Δt is the uncertainty involved in fuel flow rate.

The uncertainty involved in brake thermal efficiency is

$$\Delta(\eta_{BTH})=\sqrt{\left[\frac{\partial(\eta_{BTH})}{\partial(TFC)}\times\Delta(TFC)\right]^2+\left[\frac{\partial(\eta_{BTH})}{\partial(BrakePower)}\times\Delta(BrakePower)\right]^2} \quad (4)$$

From the calculations, it was found that the uncertainties involved in brake power, total fuel consumption, and brake thermal efficiency are ± 0.2 kW, ± 0.02 kg/h, and ± 1.2 % respectively. As per the specifications of the exhaust gas analyzer, the maximum possible error in the measurement of NOX, HC, CO, and smoke density is ± 5 %.

3 Results and Discussion

The performance and emission parameters at the standard injection timing and pressure were investigated. The variation of brake specific fuel consumption (BSFC) with load for different test fuels is illustrated in fig. 2.

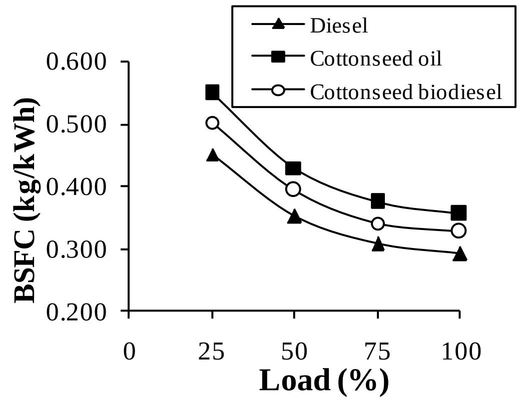


Fig. 2. Variation of BSFC with load for different test fuels

From fig. 2, it can be seen that the cottonseed oil has a higher BSFC and diesel has a lower BSFC at all loads. Compared to diesel, cottonseed biodiesel has higher BSFC. This is because of the heating value of biodiesel is lower than that of diesel. Cottonseed biodiesel requires more energy than that of diesel to develop the same power output. Similarly, due to the lower heating value, cottonseed oil has a higher BSFC as compared to cottonseed biodiesel. At full load conditions, the BSFC values of cottonseed oil, Cottonseed biodiesel, and diesel are 0.355, 0.325, and 0.291 kg/kWh respectively. The percentage increases in BSFC are 12% and 22% for cottonseed biodiesel and cottonseed oil, respectively at full load as compared to diesel. The variation of brake thermal efficiency with load for different test fuels is depicted in fig. 3.

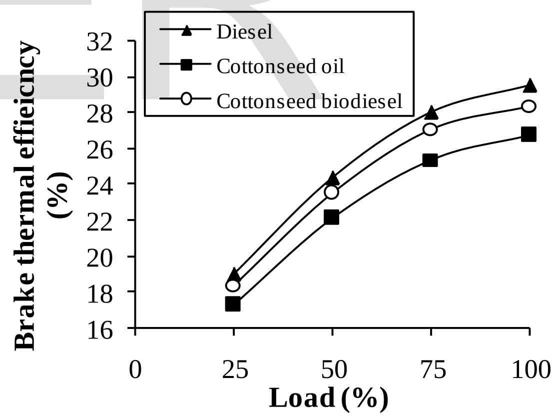


Fig. 3. Variation of brake thermal efficiency with load for different test fuels

From the figure, it can be observed that the engine with diesel operation shows a higher efficiency as compared to cotton seed biodiesel at all loads. Similarly, engine operation with cotton seed oil shows lower efficiency as compared to cotton seed biodiesel. It can also be observed that the order of magnitude of the brake thermal efficiency of the test fuels is the reverse order of the magnitude of BSFC of the respective fuels at all loads. This is due to the fact that the brake thermal efficiency is inversely proportional to the BSFC. At full load operation the brake thermal efficiency for diesel, cottonseed biodiesel, and cottonseed oil are 29.5%, 28.4%, and 26.7% respectively.

Fig. 4 describes the variation of exhaust gas temperature with load for different test fuels. It is clear that the exhaust gas temperature values are exactly the reverse order of the magnitude of the brake thermal efficiency at a given load from the fig. 3 and 4. The poor energy utilization by the engine is specified by the higher exhaust temperature, which in turn symbolize lower thermal efficiency. At a given load, the value of exhaust gas temperature of diesel was found to be lower than cottonseed oil. The exhaust gas temperature of cottonseed biodiesel lies in between diesel and cottonseed oil. At full load, the exhaust gas temperatures are 375^{0}C, 420^{0}C, and 348^{0}C for cottonseed biodiesel, cottonseed oil, and diesel, respectively. This may be due to the fact that the higher viscosity and poor volatility of Cottonseed oil lead to poor mixture formation and hence diffusion combustion phase is more dominant which prolongs the heat release process. This may lead to higher exhaust gas temperature. The increases in exhaust temperatures are 8 % and 21 % for Cottonseed oil and Cottonseed biodiesel respectively at full load, as compared to diesel.

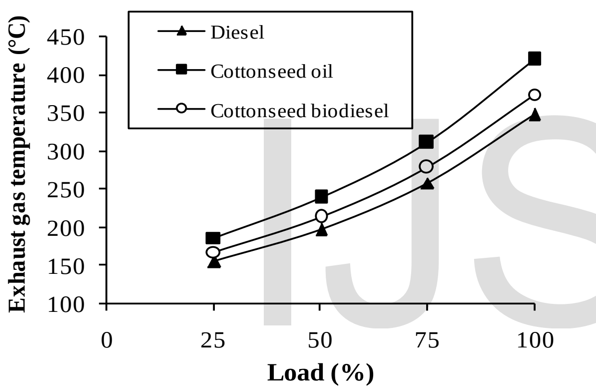


Fig. 4. Variation of exhaust gas temperature with load for different test fuels

Fig. 5 and 6 illustrate the variation of oxides of nitrogen (NO_X) and smoke with load, respectively. Cottonseed biodiesel shows a higher NO_X emission than that of diesel at full load, which can be observed from Fig. 5. Higher combustion temperatures and availability of oxygen supports the formation of NO_X. Unlike diesel, biodiesel contains oxygen. Production of more NO_X is favored by this fuel-borne oxygen, together with higher combustion temperatures, NO_X is higher for with cottonseed biodiesel than diesel fuel combustion. The cottonseed oil as compared to diesel exhibits a lower value of NO_X at full load. The decrease in NO_X emission with cottonseed oil may be believed due to the reduced premixed burning rate following the delay period. Low peak temperature and NO_X levels may be the outcome of lower air entrainment and fuel air mixing rates with the cottonseed oil. At full load, the NO_X emissions are 2048, 2189, and 1853 ppm of diesel, cottonseed biodiesel, and cottonseed oil respectively. That is cottonseed biodiesel shows an increase of 7% and cottonseed oil exhibits a decrease of 10% in NO_X as compared to diesel.

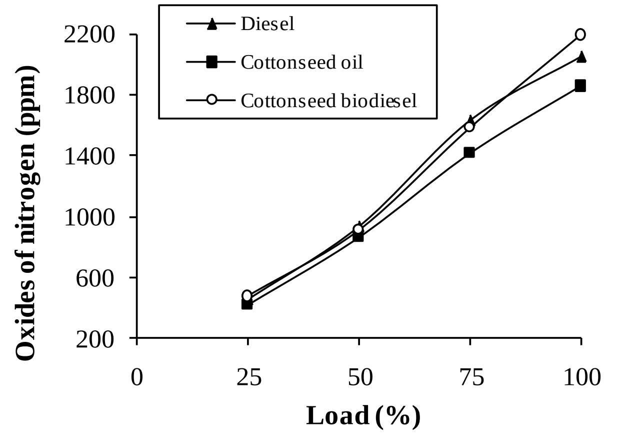


Fig. 5. Variation of NO_X with load for different test fuels

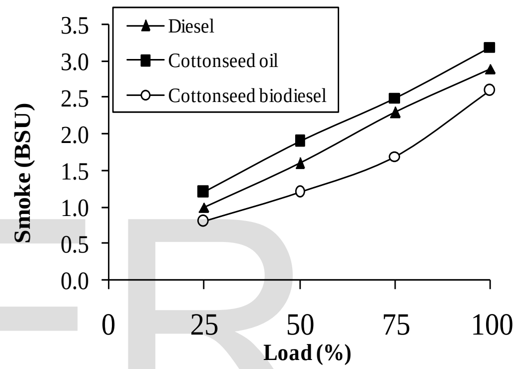


Fig. 6. Variation of smoke with load for different test fuels

It can be seen from Fig. 6 that the smoke density is 3.2 BSU (Bosch Smoke Units) with cottonseed oil and 2.9 BSU with diesel. Atomization becomes poor with cottonseed oil, due to its heavier molecular structure and higher viscosity and this may lead to a higher smoke emission as compared to diesel. As compared to diesel, the smoke emission is reduced with the use of cottonseed biodiesel (2.6 BSN). This is due to the fuel-borne oxygen in the biodiesel which can result in a better combustion. The cottonseed oil shows an increase 10.3% in smoke, as compared to diesel. Similarly at full load, cottonseed biodiesel ehibits 10.3% reduction in smoke as compared to diesel. From the above discussion, as compared to diesel, it can be observed that the cottonseed biodiesel shows a closer performance and emission results. Hence biodiesel derived from cottonseed can be a better substitute for diesel.

CONCLUSION

From the above results and discussion of the experimental investigations on a single cylinder, four stroke, constant RPM, stationary, air cooled, compression ignition engine fueled with diesel, cotton seed biodiesel, and cottonseed oil the following conclusions are drawn.

- It was found that the Cottonseed oil has a higher BSFC and diesel has a lower BSFC at all loads. The BSFC of cottonseed biodiesel lies between diesel and Cottonseed oil. The percentage increase in BSFC are 12% and 22% for cottonseed biodiesel and Cottonseed oil respectively as compared to diesel at full load.

- At full load operation the brake thermal efficiencies are 26.7%, 28.4%, and 29.5% for cottonseed oil, cottonseed biodiesel, and diesel respectively.
- At all loads cottonseed oil shows higher value and the diesel has lower value of exhaust gas temperature. The exhaust gas temperature of cottonseed biodiesel lies in between diesel and cottonseed oil. At full load, the exhaust gas temperatures are 375^{0}C, 420^{0}C, and 348^{0}C for cottonseed biodiesel, cottonseed oil, and diesel, respectively.
- At full load, the NOX emission are 2048, 2189, and 1853 ppm of diesel, Cottonseed biodiesel, and cottonseed oil respectively. That is cottonseed biodiesel confirms an increase of 7% and cottonseed oil shows 10% decrease in NOX, respectively as compared to diesel.
- The smoke intensity as compared to diesel was found to be higher with cottonseed oil and lower with cottonseed biodiesel. At full load, the smoke amount observed for cottonseed biodiesel, diesel, Cottonseed oil as 2.6, 2.9, 3.2 BSU, respectively.

It can be concluded that as compared to diesel the cottonseed biodiesel exhibits a closer performance. Hence it can be considered as a better alternative for diesel fuel.

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