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Performance Evaluation of a Diesel Engine Fueled with Methyl Ester of shea Butter

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***Abstract*—**Biodiesel as an alternative fuel for diesel engines has been developed for some three decades now. While it is gaining wide acceptance in Europe, USA and some parts of Asia, the same cannot be said of Africa. With more than 35 countries in the continent depending on imported crude oil, it is necessary to look for alternative fuels which can be produced from resources available locally within any country. Hence this study presents performance of single cylinder diesel engine using blends of shea butter biodiesel. Shea butter was transformed into biodiesel by transesterification process. Tests are conducted to compare the biodiesel with baseline diesel fuel in terms of engine performance and exhaust emission characteristics. The results obtained showed that the addition of biodiesel to diesel fuel decreases the brake thermal efficiency (BTE) and increases the brake specific fuel consumption (BSFC). These results are expected due to the lower energy content of biodiesel fuel. On the other hand while the NO_x emissions increased with increase in biodiesel content in the fuel blends, the emissions of carbon monoxide (CO), un-burnt hydrocarbon (UHC) and smoke opacity decreased. The engine performance which indicates that the biodiesel has properties and characteristics similar to diesel fuel and the reductions in exhaust emissions make shea butter biodiesel a viable additive or substitute to diesel fuel.

***Keywords*—**Biodiesel, diesel engine, engine performance and emission, shea butter, transesterification

I. INTRODUCTION

INTEREST in vegetable oils as alternate fuels, for diesel engines, dates back to 1930s and 1940s. However, their use as viable substitutes for diesel fuel was not popular as it tends to clog fuel filters due to high viscosity. Heating and blending of vegetable oils with diesel was used to reduce the viscosity and improve volatility but this does not remove the polyunsaturated structure of the oils [1]. Transesterification, which leads to the production of biodiesel, has been found to be an effective way of surmounting this problem. Despite this, the use of biodiesel has not yet become a widespread, the main reason being the cheap and yet vast supply of petroleum based fuels.

Several authors have attested to the fact that crude oil is undeniably a finite resource. However, predicting the point in time where crude oil is no longer an economically viable product is imprecise, due to the wildly varying factors influencing it. What is indisputable is there will be a date when this will occur [2]. Instability in the world crude oil market occasioned by perpetual rise in price and instability in supply due to strife in major oil-producing countries have rekindled interest in the search for an alternative. Also, the last few years has witnessed growing concern over the exhaustion of conventional energy sources in an environment that keeps on increasing its demand on liquid fuels. This fact, coupled to the increased public awareness on the impacts of fossil fuel emissions on the environment and their potential health hazards [3], and need of any country to become self-sufficient and therefore less vulnerable to shortages, embargos or geo-political considerations has renewed interest in biodiesel fuels.

Biodiesel is an organic alternative fuel that can run in a compression ignition with little or no modification, as opposed to pure oil that can require some modifications to the vehicle. Many vehicle manufacturers now cover a percentage of biodiesel usage in the warranty agreement of the vehicle. This means that a vehicle can use biodiesel without voiding the manufacturers' warranty. Biodiesel could also extend the life of your engine by 20% because it naturally lubricates the engine's moving parts cutting down on the friction created. Less friction also means less heat which in turn will reduce the frequency of heat related breakdowns [2]. Biodiesel is biodegradable meaning it will have no harmful effect on the environment in its liquid state. Biodiesel contains no harmful sulfur and is non toxic to humans or livestock. Sulfur emitted from engines burning petroleum-based fuels forms sulfur dioxide which reacts with water to create sulfuric acid, in turn creating acid rain. Biodiesel contains no petroleum based products at all, it can however be blended with any amount of petroleum fuel to create a biodiesel blend.

Despite these advantages, there are still some problems associated with using biodiesel. Although engine manufacturers may support biodiesel being used in their engines there are no long term field tests that prove that the use of biodiesel over the engines life may or may not increase the risk of premature wear to engine components. The long term effects of using biodiesel are not fully explored yet. Engine emissions are certified using either forecourt diesel or in some cases specially blended certification fuel. By using biodiesel it may affect the engine NOx emissions meaning the engine will fall outside of its certified specification [2].

Compression ignition engines which run on diesel fuel are more widely used in transport of passengers and cargo, electric power production, industry and agriculture compared to spark ignition engines. Hence greater attention is being devoted to the use of biodiesel and its blends in these engines. Biodiesel and its blends with diesel have been employed as a fuel for a CI engine without any modifications in the existing system.

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This study presents the performance and emission characteristics of diesel engine using shea butter biodiesel and its blends with biodiesel.

II. Materials And Method

A. Fuel source and specification

The biodiesel used throughout the testing was produced by Enweremadu and Alamu [4]. The biodiesel is made from shea butter by modifying a two-stage acid-base transesterification process found online [5]. The biodiesel conforms to the ASTM D6751 standard. During the acid-catalysed stage, the amount of methanol used is 20% of the volume of oil plus 60% excess methanol. One litre of crude shea butter and 40% of the required volume of methanol was measured and added to the heated shea butter at 55°C. The mixture was stirred gently for 5 min using a magnetic stirrer until it became murky. 1 ml of 95% sulfuric acid was added to the mixture. Holding the temperature at 55°C, the mixture was stirred gently for 1 h at 500-600 rpm. The heat was removed and stirring continued for another hour after which the mixture was allowed to settle for 2 h. To the remaining 60% of the methanol 4.9 g potassium hydroxide (KOH) was added to form potassium methoxide solution. 50% of this solution was added to the acid treated mixture and stirred gently for 5 min and allowed to settle for 6-12 h after which the glycerine was drained off. During the alkali-catalysed stage, the mixture was heated to 55°C and the second half of the methoxide solution was slowly stirred in, mixing at the same speed for 1 h. On completion of the reaction, the product was poured into a separating funnel and allowed to settle for 18-24 h. After separation of the biodiesel and glycerol, the fatty acid methyl ester was washed with 2 ml of 10% phosphoric acid added to warm distilled water and dried with anhydrous sodium sulphate.

The biodiesel was self-blended with the diesel fuel [6]. Splash blending is an effective and efficient blending technique that is widely used. Diesel was used splash blended with the biodiesel in a conical flask with continuous stirring to ensure uniform mixing. The biodiesel was blended with the diesel fuel at a volume base of 5%, 10% and 20%. Blends were prepared at 25^{o}C at the ambient temperature of the blending location. The names of these blends were defined by the name of the biodiesel fuel followed by the volume fraction of the biodiesel in the blend. The physico-chemical properties of the shea butter biodiesel (B100) and diesel, and the blends (B5, B10 and B20) are presented in Table 1.

TABLE I
BASIC PROPERTIES OF DIESEL, SHEA BUTTER BIODIESEL AND ITS BLENDS WITH DIESEL

Property	Diesel	B100	B20	B10	B5	Test methods
Density (kg/m³)	854	877	858	856	855	ASTM D1298
Kinematic viscosity at 40°C (mm²/s)	2.87	4.42	3.06	2.95	2.90	ASTM D445
Flash point (°C)	55	171	132	97	65	ASTM D93
Pour point (°C)	-15	3	-12	-14	-15	ASTM D97
Cloud point (°C)	-13	6	-9	-11	-12	ASTM D2500
Cetane number	50	58	56	53	50	ASTM D613
Ester content	-	95.21	-	-	-	GC method
Acid value (mgKOH/g)	-	0.28	-	-	-	AOCS Te 1a-64
Heating value (kJ/kg)	45	37.93	43.75	44.37	44.68	ASTM D240

B. Experimental set up

Performance and emission test was carried out in a single cylinder, four-stroke, naturally aspirated, and water-cooled Lombardini LDA diesel engine test rig. The specifications are listed in Table 2. The engine was directly coupled to an eddy current dynamometer which permitted engine monitoring. The engine and the dynamometer were interfaced to a control panel which was connected to a computer. The fuel is supplied to the engine by an external tank. A glass burette attached parallel to this tank was used for fuel flow measurement. The engine was run at full load and at the rated speed for all the test fuels. During the experiments, engine speed, fuel consumption and torque were measured and used to calculate the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), brake specific energy consumption (BSEC) and brake mean effective pressure (BMEP). Emission tests were carried out with Rosemount Analytical non-dispersive infrared gas analyzer (model 880A) for CO, CO_2 and NO_x. Un-burnt hydrocarbons were measured with German-made flame ionization detector, model VE7 while smoke was measured with Bosch type (model ETD02050) smoke meter. Oxides of nitrogen (NOx), Carbon monoxide (CO), Un-burnt hydrocarbon (UHC) and smoke opacity were measured for exhaust emissions at full load and rated engine speed of 1700 rpm. Tests were repeated three times and the results of the three replications were averaged and reported.

TABLE II
TECHNICAL SPECIFICATION OF THE TEST ENGINE

Engine parameter	Specification
Model	LDA 450
Number of cylinders	1
Bore	85 mm
Stroke	80mm
Injection timing	25° BTDC
Displacement volume	454 cc
Compression ratio	17.5:1
Maximum torque at 1700 rpm	28.5 Nm
Maximum power	5.5 kW

III. RESULTS AND DISCUSSIONS

A. Engine Performance parameters

Brake specific fuel consumption and brake thermal efficiency

With increase in biodiesel content in the blends, the heating value of fuel decreases. Therefore, the BSFC of the fuel blends increase with biodiesel content. The BSFC of the biodiesel and its blends is higher compared to the diesel fuel (Fig. 1). This may be attributed to the lower viscosity, lower density and higher heating value of the petro-diesel.

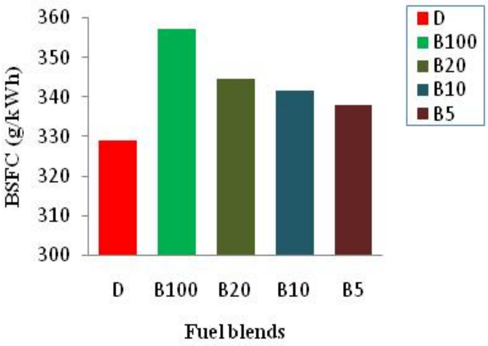

Fig. 1 Comparison of BSFC for diesel and biodiesel-diesel blends at full load

Brake thermal efficiency (BTE) is the ratio between the power output and the energy introduced through fuel injection. Thus, the inverse of BTE is BSFC. Besides their heating values, BTE is more appropriate to compare the performance of different fuels. Fig. 2 shows that the BTE of shea butter biodiesel and its blends with diesel fuel is lower compared to that of diesel fuel. The BTE of blends of the biodiesel lie between those of diesel and shea butter biodiesel. However, the decrease in BTE is not proportional to the increase in biodiesel content. The improved efficiency may be due to better lubricating properties of the blends as compared to the pure components.

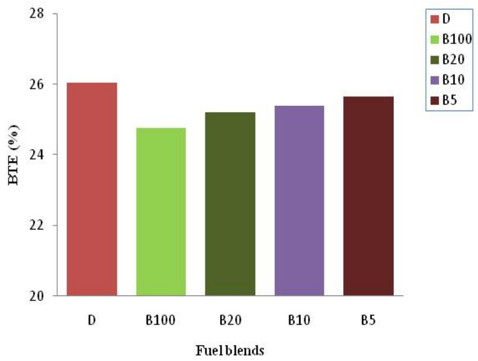

Fig. 2 Comparison of BTE for diesel and biodiesel- diesel blends at full load

B. Emission characteristics

NO_x emissions increases in proportion to the biodiesel concentration in the blend with B100 giving the maximum (Fig. 3). NO_x emission is primarily a function of total oxygen inside the combustion chamber, temperature, pressure, compressibility and velocity of sound. Invariably all biodiesel have some level of oxygen bound to its chemical structures. Hence, oxygen concentration in WCO biodiesel fuel might have caused the formation of NO_x. Being an oxygenated fuel, UCOME also supplies oxygen in addition to air inducted into the combustion chamber and this may aid the formation of NO_x. Another contributing factor maybe the possibility of higher combustion temperatures arising from improved combustion as a larger part of the combustion of UCOME and its blends is completed before TDC due to lower ignition delay.

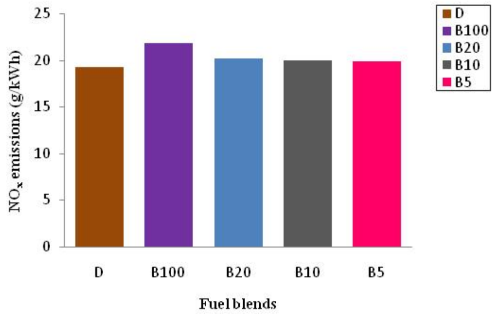

Fig. 3 Comparison of NO_x emissions for diesel and biodiesel-diesel blends at full load

Increase in NO_x emissions from biodiesel fuels may also be due to advancing of injection timing brought about by more rapid transfer of pressure wave from fuel injection pump to fuel injector to open earlier. Faster pressure wave is as a result of higher bulk modulus of compressibility and consequently a higher velocity of sound of biodiesel fuel relative to petro-diesel. Advancing injection timing in a diesel engine advances phasing of combustion process leading to a longer period of time where temperatures are conducive for NOx formation. Literature is replete with these observations [1, 7-8].

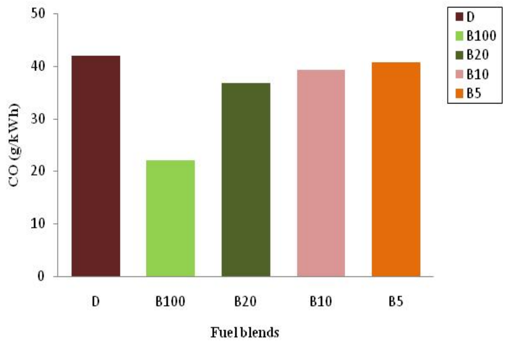

Fig. 4a Comparison of CO emissions for diesel and biodiesel-diesel blends at full load

The emissions results show that the CO, smoke opacity and UHC decrease as the biodiesel content in the blends increase with B100 producing the best emission result. The CO, UHC and smoke opacity concentrations of all the biodiesel blending percentages were less than the petro-diesel (Figs. 4a-c).

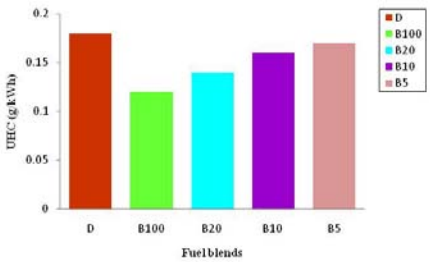

Fig. 4b Comparison of UHC emissions for diesel and biodiesel-diesel blends at full load

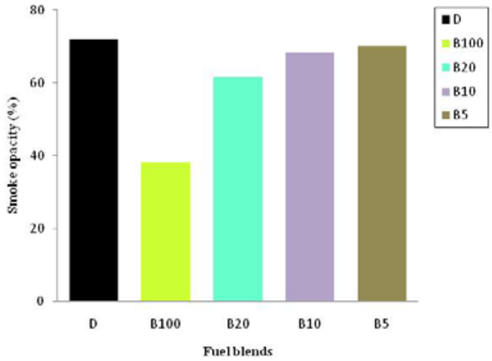

Fig. 4c Comparison of smoke opacity for diesel and biodiesel-diesel blends at full load

The decrease in CO emissions from biodiesel and its blends may be due to the additional oxygen content in the fuel, which improves combustion in the cylinder. Biodiesel also has higher cetane number and is less compressible than diesel fuel. Increased cetane number of biodiesel fuel lowers the probability of forming fuel-rich zone and the advanced injection timing. All these result in shorter ignition delay, longer combustion and increase in complete combustion reaction regions. If a fuel is less compressible, the injection starts earlier and causes longer combustion duration. These results are consistent with most published results in literature [9-12].

Since biodiesel is an oxygenated fuel, it leads to a more complete and complete combustion resulting in decrease in UHC emissions. The higher cetane number of biodiesel fuel reduces delay period leading to lower UHC emissions. Therefore, the higher oxygen content and cetane number of biodiesel-diesel fuel blends tend to reduce UHC emissions when compared to petro-diesel fuel. Similar observations have been reported by [13-15].

Since smoke is formed due to incomplete combustion, the oxygen content in B100 and its blends with diesel fuel may be more effective in enhancing better combustion, hence a decrease in smoke opacity compared to petro-diesel.

IV. CONCLUSION

This study has demonstrated that methyl ester from shea butter has a very strong potential for use as an alternative fuel in diesel engines. The performance of a Lombardini engine when fuelled with the biodiesel and its blends with diesel fuel is very similar to that when fuelled with neat petro-diesel. The main conclusions from the study are as follows:

- The brake specific fuel consumption increased with increase in biodiesel in the fuel blends.
- The brake thermal efficiency of the engine fuel with pure shea butter biodiesel and its blended fuels is lower compared to petro-diesel.
- Smoke intensity, UHC and CO exhaust emissions decreased, whereas NOx emissions increased with increase in biodiesel content in the blends.
- The experimental results preliminarily support the assertion that shea butter biodiesel can be successfully used as diesel fuel substitute in existing diesel engines without modifications but this requires long term and comprehensive tests.

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