Study of performance parameters and emissions of four stroke CI engine using solketal-biodiesel blends

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Abstract

Evaluation of performance parameters, emission and brake specific fuel consumption (BSFC) were made for different blends of solketal in soybean biodiesel with 9%, 10%, 12%, 15% of solketal (volume to volume). These experiments were performed on a single-cylinder water-cooled diesel engine at different speeds and 50% load conditions. In comparison to pure diesel, it was observed that soybean biodiesel and its blends with solketal were higher BSFC. On the addition of solketal to biodiesel higher oxides of nitrogen (NO_x) and carbon dioxide (CO₂) emissions were reported for all the blends. total hydro carbon (THC) and carbon mono-oxide (CO) emissions were found lower for soybean biodiesel and it's all four blends as compared to pure diesel and further decreases with the increase in solketal percentage in a blend. A decrease in CO and THC emissions were also observed with the increase in percentage of Solketal fuels. Solketal was found suitable and as an effective additive for biodiesel blends.

Keywords Solketal · Biodiesel · Soybean biodiesel · Emission characteristics · Performance characteristics

Abbreviations

Al ₂ O ₃	Aluminum Oxide
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CO	Carbon Mono-oxide
CO ₂	Carbon Dioxide
EGT	Exhaust Gas Temperature
HC	Hydro-Carbon
NO _x	Oxides of Nitrogen
PM	Particulate Matters
UBHC	Unburnt Hydro Carbons
THC	Total Hydro Carbon
JCO	Jatropha Curcas Oil
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
SOEE	Soybean Oil Ethyl Ester
D	Diesel

SB	Soybean Biodiesel
RPM	Revolution Per Minute

1 Introduction

Rapidly depleting fossil fuels alone would not suffice to fulfill the growing energy demand. Further deteriorating environment conditions lead to stringent environment norms that are going to more stringent in the near future. In this scenario, researchers are looking hopefully towards the alternative fuels for power generation and transport sector. Environment conditions and scarcity of fossil fuels further add in the need for less polluting and renewable alternatives. Similarly, fuel properties, bio-fuels, biodiesel, vegetable oils and petro-diesel makes them suitable alternatives for petrol and diesel. Renewable nature and low hydrocarbons and CO emissions place biodiesels at a prominent position among other alternative fuels [1].

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Biodiesels have their own problems and limitations like high viscosities which results in reduced atomization of fuel, lower volatility which causes oxidative polymerization during combustion which results in carbon ring sticking, higher gum deposition, injector choking, lubricating oil dilution, etc. and higher NO_x emissions [2].

In catalytic transesterification of oil in-which chemical reaction with alcohol produces biodiesel and also, yields alkyl based monoesters and bi-product glycerol [3]. Glycerol was used for the production of many useful pharmaceuticals and cosmetics. To promote biofuels in the transport sector new energy legislation has been passed in Europe that states that by 2020, 10% of the energy used in transport purposes should be produced from biofuels. It will definitely escalate the production of glycerol compared to its demand in cosmetics and pharmaceutical products. So to utilize the whole production the new application areas of glycerol need to be found [4]. Solketal lowers gum formation, particulate emission, oxidation stability and improves cetane number & cold flow properties. The fuel properties similar to ethanol makes solketal a promising alternative to ethanol [5].

2 Structure of paper

The section wise details of the manuscript are as follows:

2.1 Introduction

This section discuss the brief outline of reduction of fossil fuels and its effects on environment. The alternative resources for power generation and transport sector have been explained.

2.2 Literature review

This section deals with the holistic coverage of literature studies conducted by various researchers/academicians in the area of alternative fuels of petrol and diesel for power generation in different types of engines and evaluation of different emissions like CO , CO_2 and NO_x etc. The findings of the researchers in the field of biofuels have also been discussed.

2.3 Experiment & methodology

This section gives a clear insight to the research plan adopted for carrying out research work and explanation of experimental setup for the calculation of emission of CO , CO_2 and NO_x of different fuels and fuel blends. Basic fuel properties have been displayed for the experimental setup.

2.4 Results

This section presents the results obtained after performing the different experiments on engine with different percentage of biofuel w.r.t engine speed. This section also represent the comparison of brake specific fuel consumption & engine speed. The parameter used for comparing different fuels and fuel blends.

2.5 Discussion

In this section relevance of the research work has been discussed. Some important findings also explained about the biofuel used for experiment performed.

2.6 Conclusion

This section includes conclusions of the present research work conducted. This chapter also highlights all the key findings of the manuscript.

3 Literature review

Many researchers have been using ethanol, diesel and biodiesel blends with various compositions. Singh et al. noticed the efficiency of a blend of aqua & ethanol, coconut oil, with a surfactant butan-1-ol (hybrid fuel) was found similar to diesel fuel with lower exhaust emissions except an increase in CO [6]. Consumption of fuel was higher because of the low gross calorific value of hybrid fuel and these fuel can be used directly in a Direct Injection (DI) Compression Ignition (CI) engine without any changes or modifications in the existing engines. Jatropha Curcas oil (JCO) based hybrid micro-emulsion fuel containing pretreated JCO-1-Butanol-Ethanol was tested in a VCR DI CI engine and slightly higher BSFC was observed as compared to pure diesel and comparable with other oxygenated fuels (JCOB100 and JCOB20) at all loads [2]. Yilmaz observed an increase in (Hydro carbon) HC and CO emissions and reduction in NO_x emissions with the increase of ethanol percentage in the blend of ethanol & diesel while the reverse happens with biodiesel methanol and diesel blend [7]. Lower BSFC noticed for Ethanol fuel in comparison to methanol fuel. The authors investigated the effect of hydrogen addition to a CI engine fueled with the diesel fuel-waste cooking oil biodiesel (WCOB) blend (B25) on the engine performance and exhaust emissions through experiment [8].

Armas et al. used 10% ethanol and 16% butanol blends and observed higher NO_x and THC emissions with reduced

CO and particulate matter (PM) emissions [9]. On comparison of biodiesel blend with 5%, 10% and 15% of methanol or ethanol with Euro V diesel fuel and pure biodiesel, Zhu et al. found a reduction in NOx and PM emissions of a diesel engine for blended fuels [10]. Better results were observed for methanol blends. 5% blend could reduce the CO and HC with an improvement in brake thermal efficiency (BTE). With the increase in the proportion of alcohol in blends NOx and PM were decreased. Younus et al. investigated tyre pyrolysis oil and diesel blend with additives (Ethanol and Ethyl Hexyl Nitrate) and reported an increase in BTE in proportion to blend percentage (T10, T20, T30) and a decrement in BSFC, CO, HC and NOx emissions than pure diesel [11]. The emission and performance characteristics of a diesel engine using Karanja oil/ Diesel as fuel by varying the proportion of Karanja oil from 10 to 100% in the blend and highest BSFC and exhaust gas temperature (EGT) for pure biodiesel at all loads were reported. Further, fewer HC emissions were observed for biodiesel as compared to diesel. Yasin et al. conducted experiments on biodiesel-ethanol-diesel blends (B20E5D75, B20E10D70, B20E15D65, B20E20D60) and reported higher BSFC of the blends in comparison to diesel and an overall reduction in the NOx emissions when higher ethanol concentration was used but increase in CO emission for all the blends [12]. Properties of castor oil biodiesel were studied by Berman et al. and concluded that this blend can be used as an alternative when blended with petrodiesel but the highest blending limit was 10% (of castor biodiesel) only because of very high ricinoleic acid [13]. Optimal operating parameters of the engine was analyzed by incrementing and decrementing the compression ratio upto CR18 and CR17 respectively to found the effect of jojoba biodiesel-diesel blends on emission and performance phenomenon in the four stroke single cylinder compression ignition engine [14]. The authors performed the test on petro-diesel combustion engine to see the effects of a novel ternary blend of n-butanol and castor oil methyl ester (COME) and obtained optimum blending proportion which can simultaneously reduce UHC (Unburnt Hydro carbon), CO and NOx without affecting engine performance [15]. Kumar et al. observed a significant decrease in HC, & CO emission with most types of biodiesel and no observation specifically to NOx emission was reported [16]. NOx emission increases with the decrease in chain length for saturated esters. Most highly unsaturated fuels: soybean and canola oil exhibit the highest NOx, poor oxidation stability, good cold flow properties and viscosity. In comparison to the diesel fuel, soybean oil & palm oil and waste frying oil presented the lowest emissions [17]. B20 (20% soybean biodiesel and 80% diesel fuel) blend offered lowest fuel consumption. For Biodiesel blend, 9%, 10%, 23% reduction in CO, NOx and SO2 emissions respectively with a 22%

increase in CO2 emissions were reported. On testing of pure soybean oil, crude degummed soybean oil and soybean oil ethyl ester (SOEE) as a fuel in a diesel engine. A reduction of 21% in HC and 20% reduction in PM, 24% reduction in CO, 15% increase in NOx and 7% increase in fuel consumption, are witnessed by Osborne et al. in an engine fueled with biodiesel [18]. At the same injection timing, Kim et al. reported higher NOx and lower HC & CO emissions for soybean biodiesel fuel in comparison to diesel [19]. Faster ignition, smaller particulate diameter and lower value of peak combustion pressure for soybean biodiesel were also reported. Low emissions have been reported when solketal is added up to 15%.

Habibullah et al. investigated performance and emissions characteristics in diesel engine with the use of palm or coconut biodiesel blend and their different combination namely PB20, CB20, PB5CB15, PB10CB10 and PB15CB5 as different fuels [20]. In comparison to diesel, these blends produced higher BSFC (3.24% to 4.07%) and lower engine brake power (0.6% to 1.72%). NOx emissions increased from 1.79% to 4.49% for all the biodiesel blends into consideration. The reason was high combustion temperature and presence of fuel-borne oxygen in the blends. The HC and CO and emission were also reduced by 13.54–23.79% and 3.36–7.01% respectively. In this work, the effect of 1-Hexanol on engine parameters has been studied to improve the combustion, performance and emission characteristics of CI engine to know the best possible injection time [21]. Jayaraman et al. prepared blend without liquid additives showing better performance along with 6% of DEE blended fuel [22].

Hosseini et al. evaluated the effects of the addition of 30, 60 and 90 ppm of alumina (Al_2O_3) nano-particles to 5% and 10% biodiesel from waste cooking oil (B5 and B10 blends) on a single-cylinder CI engine [23]. Optimized performance and exhaust emission seem to be produced by B10AL90 blend. In general, the addition of catalyst increase the power (5.36%), torque, NOx (43.61%), EGT (5.80%) and reduces the CO (2.94%) & UBHC emissions (20.56%) and specific fuel consumption (14.66%) as compared to diesel fuel.

Celik and Ozgoren found 45.77% increased CO2 emissions, 48.88% decreased in CO emissions, 46.03% decreased smoke emissions, besides a very high increasing rate of NOx in the blend of soybean oil (15%) and hazelnut methyl Ester (15%) with diesel fuel (70%) as compared to diesel [24]. Soybean crude Oil-based biodiesel prepared by alkaline catalyzed transesterification was studied by Qi et al. [25]. A higher viscosity and flashpoint for biodiesel than that of pure diesel were observed especially at low temperatures. Owing to shorter injection delay combustion for biodiesel starts earlier at all engine loads. Higher BSFC of biodiesel was noticed in comparison to diesel.

Under full load speed characteristics, the emission of NO_x, CO, HC and smoke were decreased by 5%, 27%, 27% and 52% respectively. Authors [26] investigated that while using biodiesel in addition to Al₂O₃ in different concentrations such as 25, 50 and 100 ppm and found that while using 25 ppm is suitable for low emissions and better brake thermal efficiency in a diesel engine.

Though a large number and growing literature were available on different biodiesel and their blends yet comparatively very less work was reported on solketal-diesel blends.

4 Experiment and methodology

In this study, different blends of soybean biodiesel with solketal are used. Test fuels are diesel (D), soybean biodiesel (SB), SBS9 (9%S, 91%SB), SBS10 (10%S, 90%SB), SBS12 (12%S, 88%SB), SBS15 (15%S, 85%SB). All tested are conducted on three different engine RPM (1200, 1500 and 2000) and at 50% load. The basic fuel properties of diesel fuel, soybean biodiesel and solketal are tabulated in Table 1. No modification on the diesel engine for the tests was made. The results are averaged for four times repetition engine tests.

A single-cylinder, 4-stroke, multi-fuel, water-cooled research engine manufactured by Kirloskar Oil Engines, having 87.5 mm bore, 110 mm stroke, 661 cc capacity, 3.5 kW @ 1500 RPM rated power for diesel and compression ratio range from 12:1 to 17:1 with injection variation is used for experiments. A water-cooled eddy current type dynamometer with a loading unit is provided for loading of the crankshaft. The loading unit consists of a strain gauge type load cell with range (0–50 kg) and a 230 V AC digital load indicator of range (0–50 kg). The fuel measuring unit, manometer, transmitters for air and fuel flow measurements, process indicators and engine indicator is installed as standard fittings of setup. Two rotameters and a calorimeter are provided for cooling and

flow measurements of water respectively. All the data is analyzed by "Engine soft", an engine performance analysis software. The exhaust gases namely CO, THC, CO₂ and NO_x are analyzed by AVL gas analyzer. The image of the experimental setup image is shown in Fig. 1.

5 Results

Figure 2 represents the comparison of brake specific fuel consumption & engine speed. The parameter used for comparing different fuels and fuel blends was Brake Specific Fuel Consumption (BSFC). Figure shows that as the BSFC increases with the engine speed. Different colour bar shows different types of blend and their variation with respect to BSFC and engine speed. SBS represents soybean biodiesel and solketal.

The variation of CO emission at various values of engine speed for diesel, soybean and all other four blends have been presented in Fig. 3. It can be observed from figure that the CO emission is highest in case of diesel, so it is not a good option as fuel. But with different blends of solketal, CO emission reduced upto the half of emission as compared to the diesel.

The comparison of CO₂ emissions with engine speed for different fuels were shown in Fig. 4. CO₂ emission is the main exhaust emissions and not responsible to the air pollution however it is a major greenhouse gas. The CO₂ emission decreases with increase in engine speed. But it is minimum for diesel fuel as compared to the other blends of fuel for all engine speeds.

Figure 5 represents the variation of NO_x emission with the engine speed. NO_x emission are unwanted emissions and the main reason for this emission is oxygen in air. Unlike to previous figures, NO_x emission increases for

Table 1 Basic fuel properties of test fuels

Fuel	Density (15 °C, kg m ⁻³)	Viscosity (40 °C, mm ² s ⁻¹)	Higher Heating Value(MJ kg ⁻¹)	Flash point(°C)
D	831.7	2.58	45.98	63
SB	919.7	5.06	39.10	140
SOLKETAL	1071.1	5.21	25.91	84
SBS9	919	4.42	41	88
SBS10	919.43	4.43	40.43	89.4
SBS12	921	4.47	39.31	91.1
SBS15	923	4.52	37.32	92

Fig. 1 Experimental setup

Fig. 2 Comparison of brake specific fuel consumption & engine speed **Fig. 3** Comparison of CO emissions with engine speed **Fig. 4** Comparison of CO₂ emissions with engine speed

Fig. 5 Comparison of NO_x emissions with engine speed

biodiesel with solketal and its blends as compared to the diesel. But for all other fuels, it decreases for higher value of engine speed.

The comparison of hydrocarbon emission with engine speed has been shown in Fig. 6. The main reason of the hydrocarbon emissions is incomplete combustion. It is clear from figure that the rate of hydrocarbon emission is the highest for diesel and were not significantly affected by the engine speed.

6 Discussion

Solketal and soyabean biodiesel blends have higher flash points which are helpful in the proper handling of the fuels. Also, it has been observed that fuel consumption is higher for all the blends due to an increase in density and viscosity. BSFC is one of the important criterion for comparing different fuels and fuel blends used in engines. Results indicated that BSFC values for blends increases as the engine speed increases. Owing to more density of biodiesel blends than diesel, it also found that higher BSFC values for biodiesel and its various blends with solketal than that of pure diesel. On addition of solketal to biodiesel, BSFC values for different blends increases

Fig. 6 Comparison of THC emissions with engine speed

with the increase of proportion solketal in the blends and being highest for SBS15 blend at all engine speeds. A calibrated AVL gas analyzer was used for measuring of total hydro-carbons (THC), oxides of nitrogen (NO_x), carbon monoxides (CO), carbon dioxide (CO_2) emissions. After performing the experiments, it was found that the CO emission is lower for soybean and other various solketal and biodiesel blends as compare to the diesel. This is due to the presence of solketal in fuel which in turn increases the oxygen level in fuel. Therefore, as the percentage of solketal in blend increases, the CO emission will get lowered. CO emission is also depends on the engine speed. As CO emission reduces with the increase in engine speed for diesel, soybean and all other four blends used in the study. The lowest CO emissions were reported by SBS15 blend at 2000 RPM. SBS15 blend showed approximately 47% lower CO emissions than diesel at 1200 RPM.

As CO_2 is one of the major greenhouse gases and it's been noted that CO_2 emissions decrease with the increase of engine speed at constant load. The value of CO_2 emission for biodiesel and solketal & its blends is higher than that of diesel at various engine speeds. The highest value of CO_2 emission for SBS15 blend is achieved at 1200 RPM. On the other hand, lower CO_2 emission is for pure biodiesel at all engine speeds. NO_x emission was directly affected by combustion temperature, residual nitrogen in the air and the oxygen content in the fuel. Higher NO_x emissions have been found for biodiesel and its blends with solketal in comparison to the diesel. NO_x emissions increase with the rise of solketal percentage in the blend and decreases with increasing the engine speed. NO_x emissions are approximately the same for all solketal and soybean biodiesel blends. Hydrocarbons are produced due to incomplete combustion of hydrocarbon fuels. It was found that THC emissions for biodiesel and biodiesel blends with solketal are much lower than that of pure diesel. THC emissions also reduces with increasing the percentage of solketal in blend being lowest for SBS15 blend. THC emissions reduce up to 63% using SBS15 blend in the engine at 1200 RPM. A significant reduction in THC is produced by using solketal as a fuel additive with biodiesel.

7 Conclusion

A comprehensive experimental study has been carried out on BSFC and exhaust emissions of solketal biodiesel. Characterization of test fuels results that solketal addition to biodiesel increases flash point which helps in the proper handling of fuel. Emission results conclude that CO and THC emissions were lower for biodiesel and various solketal blends. These emissions were reduces with the engine speed and percentage of solketal in the blend.

All the blends and biodiesel showed higher NO_x and CO_2 emissions at all engine speeds and increases with an increase in solketal percentage. BSFC for all four blends come out to be higher than diesel. It can also be concluded that solketal can be utilized as a fuel additive with biodiesel in a diesel engine without any alteration in the engine. Fuel additive may be the possible avenue for the utilization of solketal.

Further research work related to combustion characteristics, injection timing and exhaust emissions is the need of time to be carried out at different engines at different load conditions at different engines and with different biodiesel and solketal blends as indicated by the present study. A very few studies on solketal-gasoline fuel blends in the spark-ignition engine are observed and the need for more such studies is felt.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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