Comparative Study on CI Engine Performance and Emissions using a Novel Antioxidant Additive

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ABSTRACT

The depletion of conventional energy sources and environmental pollution related to use of these energy sources make biodiesel as a renewable replacement to diesel. The biodiesel can be used as an immediate replacement to fossil diesel as its properties are comparable to diesel. The main drawback of the biodiesel is its lower oxidation stability and prone to microbial growth which degrades the properties of biodiesel during storage. However, these problems can be overcome by adding suitable additives to the biodiesel. The non-edible neem oil is one of the feedstocks used for biodiesel in India. The neem biodiesel has lower oxidation stability and hence it is necessary to add suitable additive. The eucalyptus oil has better antioxidant and microbial inhibition properties and hence it was used as an additive in this work. The effect of adding this additive on the biodiesel properties, engine emissions and performance were studied. The engine tests were conducted on a compression ignition engine at different loads with various concentration of eucalyptus oil. The engine performance indicates that the thermal efficiency of the engine with biodiesel is lower than the diesel fuel while the engine exhaust emissions like HC, CO and smoke were lower with the biodiesel. The use of eucalyptus oil as an additive to the biodiesel at full load increases the engine thermal efficiency by 3.08%. Also, it lowers the engine exhaust emissions except NOx emission.

Keywords: *Biofuel; Biodiesel; Eucalyptus Oil; Engine Tests; Emissions*

Introduction

The world's energy demand is increasing due to globalization and urbanization and it is reported that the oil resources will be depleted by 2030

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[1]. It is reported that the fossil fuel reserves of crude petroleum oil will be depleted in 35 year [2]. The enhanced manufacturing activities and increase in vehicle population increases the demand for petroleum products in India. The data released by India government indicates that the demand of oil between April 2015 and March 2016 increases by 10.9 percent. In India, the local and global car makers are introducing new car models which indirectly increase the fuel demand. An analysis shows that the 70 percent of diesel is consumed in the automobile sector. It also reports that the diesel consumption (28.48%) is by three wheelers, cars and utility vehicles are highest as compared to the agriculture sector [3].

The growth of the Indian economy is approximately 7 percent since 2000. The CO_2 emission emitted by the automobile vehicles is approximately 13 percent. The government of India wants to reduce CO_2 emission by following a sustainability method. This method prefers use of biofuel as a replacement to the fossil fuels. India is one the largest user of petroleum products and is reported that the primary energy demand will be double in India by 2030. It was estimated that if India's GDP increases by one percent then the demand for crude oil will increase by 2.89% [4].

The increase in crude oil prices and expenses related to oil imports force the government to opt for alternative fuels. India's bio-fuel policy suggest use of biofuels as a renewable replacement to petroleum products as it will reduce oil imports from other countries and indirectly improve the energy security [5]. This policy has created awareness among common people about the use of biofuels as substitute for the fossil fuels, in particular, biodiesel and bioethanol. The government policies have also boosted the production of biofuels which indirectly helps the rural economy.

The vegetable oil is converted into biodiesel by transesterification method. The methanol and ethanol are used for biodiesel production. The transesterification reaction is affected by the reaction time and temperature, type of catalyst and molar ratio of alcohol to oil [6]. The homogeneous catalyst are used for transesterification reaction, however in recent years heterogeneous catalyst are preferred. The proper selection of alcohol and catalyst is important to get higher biodiesel yield and to reduce the cost of biodiesel [7]. A significant research work has been carried to find suitable reusable solid catalysts and studied on effect of the structural properties of various solid catalysts on biodiesel yield [8]. The biodiesel wastewater contains excess catalyst, alcohol, glycerol and soap and hence it has to be purified to remove these unwanted substances [9].

The engine combustion characteristics are affected by the type of biodiesel blend and hence lower biodiesel diesel blend is preferred [10]. The viscosity of the biodiesel is higher and hence it results in coarse atomization and poor spray formation. The fuel injection system has to be modified if biodiesel is used as fuel in diesel engine due to higher cloud point of the biodiesel. The ignition delay period of biodiesel is higher than the diesel. The biodiesel causes lower engine exhaust emissions like hydrocarbon (HC), carbon monoxide (CO) and smoke [11]. The type of biodiesel feedstock affects the biodiesel quality and directly affects the engine combustion performance and engine exhaust emissions.

Few researchers used biodiesel as fuel in compression ignition engine and suggested that the engine process variables should be optimized to get lower emissions and higher thermal efficiency [12]. The biodiesel's oxidation stability is low due to fatty acids containing double bonds. This causes formation of insoluble substances, sediment and gum. These substances may cause depositions in the fuel injection components, engine combustion chambers, filter plugging and injector fouling [13]. Few researchers reported that the biodiesel properties changes during storage and the value of viscosity and acid value increases with storage period [14]. The thermal and oxidative degradation of the biodiesel results in deterioration in fuel properties [15]. Hence suitable natural and synthetic antioxidant additives are developed and mixed with biodiesel with the concentration various from 250 to 1000 ppm [16].

Ana Carolina Roveda et al. [17] used various synthetic antioxidants like butylated hydroxy toluene (BHT) and propyl gallate (PG) and carried out accelerated storage study by varying storage temperature from 85°C to 110°C. They used rancimat method to determine the oxidative stability of PG and BHT with DHQ. They reported that the combinations of the synthetic antioxidants are effective as compared to individual compounds and the optimum mixing the additive cost. Gabriela Menegon Buosi et al. [18] used the combination of natural extracts of rosemary, oregano and basil with antioxidant (TBHQ, BHA and BHT), to improve the soya bean biodiesel oxidation stability. They reported that the best formulation is 50% rosemary, 12.5% oregano and 37.5% basil. The mixing of antioxidants to the biodiesel influences the engine combustion, thermal efficiency and engine exhaust emissions significantly [19]. The natural antioxidants derived from catechin, curcumin and quercetin are better than the butyl hydroxyanisole for the cotton seed oil biodiesel. However the interactions among the extracts varied with the total concentration [20]. The addition of natural additives such as L-Ascorbic Acid 6-palmitate, caffeic acid and tannic acid to plant-seed derived biofuels improves the thermal and oxidative stability and viscosity of the canola biodiesel [21]. The poor oxidation stability, cloud and pour ponits of the karanja oil biodiesel was improved with natural additive derived from *T. cordifolia* stem [22].

The clove oil was used as natural antioxidant for the cotton seed oil biodiesel and the results shows that the oxidation stability increases with increase in addition of clove oil. The addition of clove oil to biodiesel increases the brake thermal efficiency by 4.71% at full load. Also it significantly affects the CO, HC, NOx and smoke emissions [23]. The higher alcohols such as decanol and hexanol can be used as partial subjects diesel.

The engine tests conducted with ternary blends of diesel-biodiesel- alcohols revealed that thermal efficiency of ternary blends were better than biodiesel. Also this ternary blends produces lower hydrocarbon, smoke, carbon monoxide emissions as compared to both biodiesel and diesel [24].

During the storage of biodiesel blends, microbial growth takes place and it may cause production biological mass at the interface of fuel-water. This affects the properties of the biodiesel blend and there is a chance of corrosion of tanks and pipes due to metabolism of these microorganisms which release acids [25]. Hence it is necessary to add additives to inhibit the microbial growth.

Barra et al. [26] reported that the chemical composition of eucalyptus oil changes depending on the origins and their study shows the major components of eucalyptus oil are spathulenol, 1,8-cineole, beta-phellandrene, cryptone and p-cymene. Their results show that the eucalyptus oil has antifungal activities at low doses and also it has better antioxidant activity. Huey-Chun Huang et al. [27] reported that the eucalyptus oil has better antioxidant characteristics and reduces the intracellular reactive oxygen species levels. It is also reported that the eucalyptus leaf oil can be used as antioxidant due to its ability to inhibit the free radicals [28].

Gitte Sørensen et al. [29] investigated the microbiological stability of biodiesel blends and their results show the bacterial growth in the incubations of fuel blends. Juan-Manuel Restrepo-Flórez [30] used a simulation work to study the influence of biodiesel on a microbial population and reported that the biodiesel has higher microbial growth. From this literature review, it is observed that the biodiesel is prone to oxidation and microbial growth deteriorate the properties of the biodiesel and hence suitable additive to be added to avoid these problems. Hence in this work, we have used eucalyptus oil as the additive and studied its effect on the compression ignition engine. The demand of edible oil is high in India and hence government of India promotes non-edible oils as biodiesel feedstock. Among available non-edible oils, neem oil has significant potential and also easily available in the market. However, the neem biodiesel has lower oxidation stability and hence in this study, engine tests were conducted to study the impact of eucalyptus oil on the neem biodiesel.

Materials and Methods

The neem oil available in the open market was purchased and filtered to remove impurities. The acid value of the neem oil was estimated, and it was 64 mg KOH/gm. Hence the neem oil was subjected two step transesterification involving acid esterification and base transesterification, to produce biodiesel. The low-cost alcohol (methanol) was used as solvent. The sulfuric acid and potassium hydroxide were used as acid and base catalyst respectively. The properties of the neem biodiesel like flash point, viscosity, density and calorific value were determined as per the ASTM methods and compared with the fossil diesel. The eucalyptus oil was mixed with the neem biodiesel with the concentration of 250, 500 and 750 ppm. A compression ignition engine was modified to work as experimental setup using suitable instrumentation. The engine trials were conducted to study the impact of eucalyptus oil on the engine exhaust emissions and performance.

The engine exhausts emissions such as CO, HC and NO_X were measured and recorded using an MRU make (delta 1600 L model) exhaust gas analyzer. The infrared measurement technique was used to measure CO and HC emissions. An electro chemical sensor was used to measure NO_X emission.

Engine Test Setup

A series of engine tests were conducted on a four stroke, compression ignition engine which cooled by water. The details of the test engine are shown in the Table 1. The engine load was varied using a swinging field electrical dynamometer. For baseline data, engine experiments were conducted with diesel and important engine performance parameters and engine exhaust emissions were recorded after the engine reaches steady state condition and engine load was varied from no load to full load. After the engine tests, the fuel was changed, and similar procedure explained above was carried out and observations were recorded. Figure 1 shows the engine experimental setup.

Table 1: Test engine details

Item	Details
Make	Kirloskar
Model	TAF 1
Rated Power (kW) at 1500 rpm	4.4
Rated Speed (rpm)	1500
Compression Ratio	17.5 : 1
Injection Timing (degree)	23.4 degree bTDC
Injector Nozzle Opening Pressure (bar)	200
Fuel Injection	Direct Injection
Stroke X Bore (mm)	110 X 87.5
Other Details	Naturally aspirated CI Engine

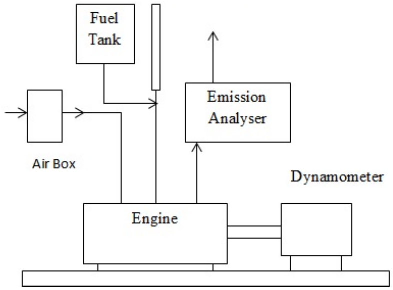

Figure 1: Engine experimental setup.

Error Analysis

The error analysis was carried out and the error of various instruments was shown in the Table 2.

Table 1: Error analysis

Instruments	Accuracy	% Uncertainty
Load measuring unit	± 0.1 kg	± 0.10
Fuel measuring unit	±0.1 cc	± 0.20
Digital stop watch	± 0.6 sec	±0.03
Speed measuring unit	± 10 rpm	± 0.10
EGT measuring unit	± 1°C	± 0.11

Results and Discussion

The neem oil was converted into biodiesel using two-step transesterification process. The fuel properties like flash point, density, dynamic viscosity and calorific value of the diesel, biodiesel and biodiesel added with eucalyptus oil were determined as per ASTM method. The transesterification reaction is shown in the Figure 2.

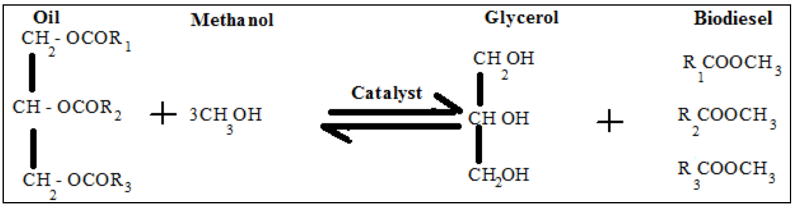

Figure 2: Transesterification Reaction

Table 3 compares important properties of the fuels. A slight difference in the properties is observed with biodiesel (B0) and biodiesel added with eucalyptus oil. Since the eucalyptus oil is added in terms of ppm, the variation of properties is small. However, the properties of diesel are better than the biodiesel.

Table 3: Comparison of fuel properties

Property	B0	B250	B500	B750	Diesel
Dynamic Viscosity (mm^2/s)	4.8	4.8	4.84	4.89	3.5
Calorific Value (MJ/kg)	38.4	38.4	38.1	38	43.2
Flash Point (˚C)	147	148	150	153	71
Density (kg/m^3)	861	861	863	866	847

The engine tests were conducted with diesel, biodiesel and biodiesel with different concentrations of eucalyptus oil. The addition of eucalyptus oil affects the engine emissions and performance. The engine performance is represented by the term brake thermal efficiency which indicates how the energy possessed by the fuel is converted into mechanical energy. The impact of additive on the brake thermal efficiency of the diesel engine at various loads is indicated in Figure 3. Figure 3 shows that the engine's brake thermal efficiency increases with increase in engine load. Among the various fuels, the brake thermal efficiency is higher with diesel as the engine is designed for diesel. The brake thermal efficiency is lower with the neem biodiesel due to its lower volatility and slightly higher viscosity. The effect of eucalyptus oil on biodiesel is small at low loads. However, at higher loads, eucalyptus oil enhances the brake thermal efficiency. The brake thermal efficiency is lower with eucalyptus oil concentration of 750 ppm. However, the eucalyptus oil with the concentration of 500 ppm provides better thermal efficiency as compared to the 750 ppm.

The engine combustion temperature is directly influencing the engine exhaust gas temperature (EGT). The changes in EGT of the engine at different load with various fuels are depicted in Figure 4. The engine load affects the EGT and eucalyptus oil also impact the EGT. The higher fuel consumption at higher loads causes higher EGT at higher loads. The EGT is higher with biodiesel as compared to diesel fuel due to higher ignition delay period of the biodiesel. However, the addition of eucalyptus oil reduces the EGT of the engine. The variation in EGT of different eucalyptus oil concentration is small.

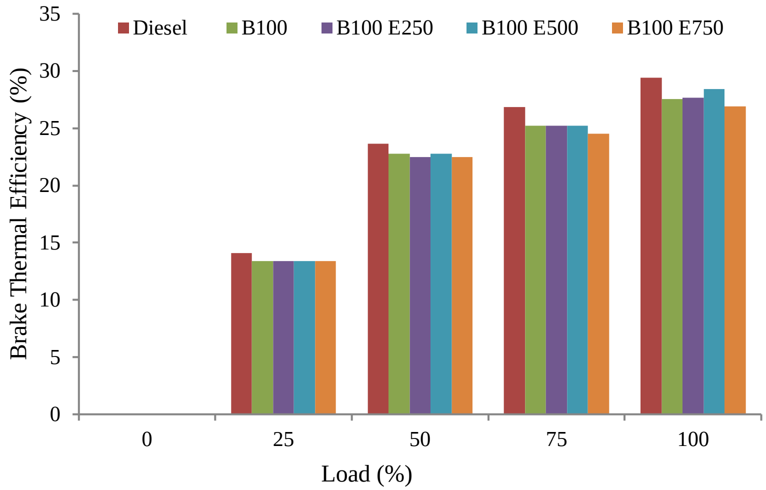

Figure 3: Brake thermal efficiency versus load.

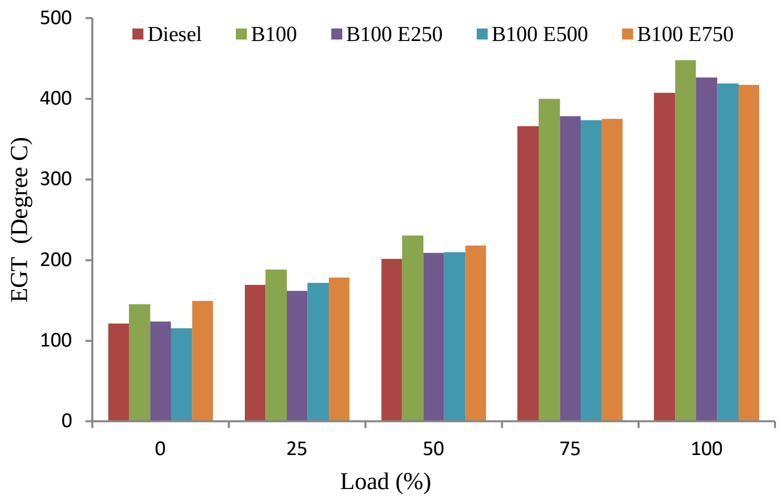

Figure 4: EGT versus load.

The impact of eucalyptus oil on engine un-burnt hydrocarbon (UBHC) emission is indicated in Figure 5. The engine consumes more amount of fuel to produce higher power. The higher fuel supply increases the UBHC emission. Figure 4 depicts that the engine UBHC emission increases with the increase in the load and UBHC emission is high at higher loads. The biodiesel contains oxygen in its molecular structure and hence engine's UBHC with biodiesel is lower than the diesel fuel. At low loads, the variation in UBHC is low. However, the eucalyptus oil concentration of 500 ppm produces lower UBHC emissions as compared to the diesel and other concentrations. However, the additive concentration of 750 ppm causes higher UBHC with reference to other concentration.

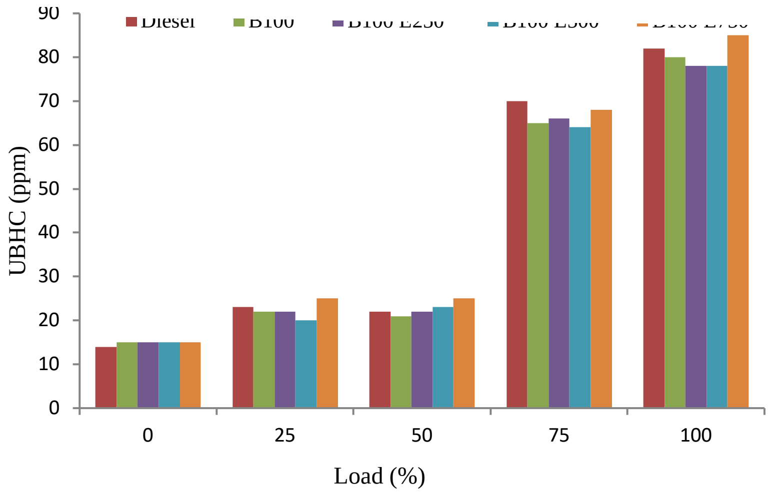

Figure 5: UBHC versus load.

The variation of engine's CO emission at various load is depicted in Figure 6. The CO emission indicates the incomplete combustion of the fuel in the engine. The engine's CO emission increases with the increase in the load. The biodiesel is an oxygenated fuel and hence engine's CO emission with biodiesel is lower than the diesel fuel. It is noticed that at higher loads, the CO emission of the biodiesel is lower than the biodiesel added with the eucalyptus oil. The higher eucalyptus oil concentration of 750 ppm provides higher CO emission.

The variation in engine's NOx emission with different fuels and at various engine loads is indicated in Figure 7. The engine's NOx emission increases with the increase in the engine load due to higher consumption fuel at higher loads. However, the engine's NOx emission is higher with biodiesel, and also at all loads. The additive added biodiesel significantly emits lower NOx emission with reference to neat biodiesel. The NOx emission is lower with the additive concentration of 750 ppm. The reduction in NOx emission is due to the production of hydrocarbon free radicals which reduced the formation of NOx during combustion process.

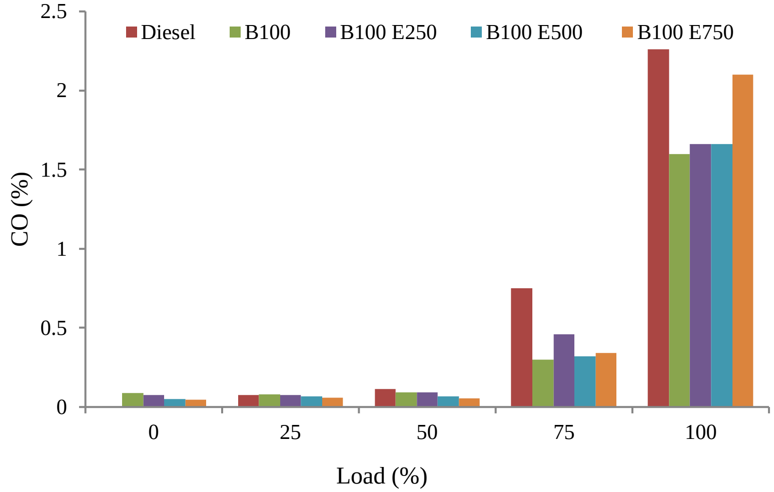

Figure 6: CO versus load.

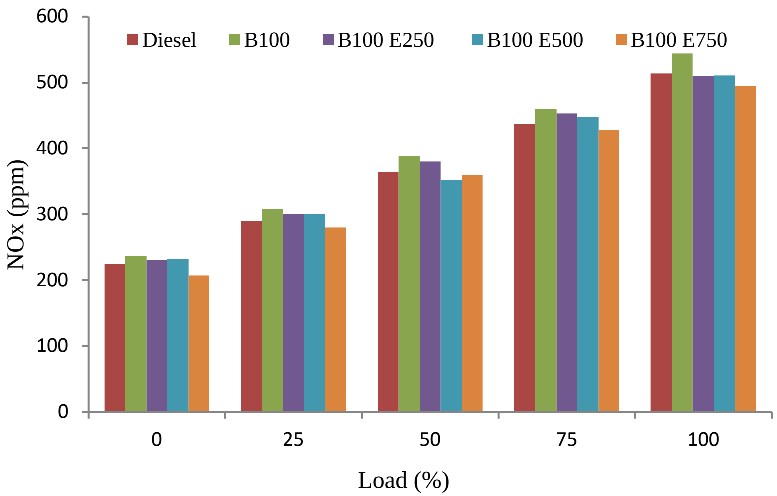

Figure 7: NOx versus load.

Conclusion

From the fuel property analysis, it was observed that the neem biodiesel properties were better than the raw oil and comparable to the diesel fuel. The viscosity of the raw oil was reduced drastically transesterification. The engine tests results show that the eucalyptus oil impact the thermal efficiency and performance of the diesel engine. The higher eucalyptus oil concentration of 750 ppm causes lower thermal efficiency. However other concentrations result in better thermal efficiency and engine performance at higher loads. The addition of eucalyptus oil with the concentration of 500 ppm results in 3.08 % increase in thermal efficiency at full load as compared to the biodiesel. Also, it was observed that eucalyptus oil concentration of 500 ppm reduces the carbon monoxide and unburnt hydrocarbon emissions as compared to other concentrations. A slight difference in NOx emission was observed with various concentrations of eucalyptus oil. Hence, we conclude from this work that the eucalyptus oil can be used as natural additive to the neem biodiesel.

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