Comparative study of low NO\(_x\) and CO\(_2\) emission novel biodiesels on direct injection CI Engine

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Abstract. In this experimental study an attempt is made to find out a biodiesel, whose NO\(_x\) and CO\(_2\) emissions are less and encouraging. Vegetable oils namely Babul oil (Acacia Arabica), Tung Oil (Aleurites fordii) and Grape seed oil (vitis vinifera) were transesterified to reduce their viscosity. These biodiesels were studied as fuel in direct injection 3.7 kW, 1500 rpm with electrical resistance loading. Experiments were conducted at constant speed of 1500 rpm at different percentages of full load of the engine. Out of these three, Grape seed oil methyl ester (GSME) has its performance closer to that of diesel fuel followed by Babul Oil Methyl Ester (BOME) and Tung Oil Methyl Ester (TOME). The brake thermal efficiency of GSME is marginally lower than that of Diesel at full load. The CO2 emissions of these biodiesels were 13%, 17% and 29% lower than that of diesel fuel emissions at full load for BOME, GSME and TOME respectively. The NO\(_x\) emissions of BOME and TOME were lower by 22% and 27% lower than that of diesel fuel. However the smoke emissions are higher than that of pure diesel operation of the engine.

1. Introduction

Biodiesels form the economically viable solution for the energy crisis faced by the world now. Especially this subcontinent is blessed with varieties of vegetation that forms the resource for novel biodiesels or biofuels. Emission wise also, many new biofuels are emerging as promising alternatives to existing engine fuels. In many studies conducted the after treatment methods are adopted for reducing emission after combustion in the cylinder. There are some fuels which emits lesser without any after treatment. Many methods such as blending with emission reducing agents such as bioethanol, pentanol, iso-butanol, kerosene, EGR and HCCI modes of operations are adopted for emission reduction methods.

Alirezha [1] conducted experiments on a 4 cylinder 1800 rpm CI engine with four blends of waste frying oil biodiesel. The CO concentrations were found to decrease from 0.04% to 0.035% with increase in engine load for all the blends. Haoye etal [2] conducted experiments on a single cylinder CI engine with biodiesel and fuel additive Polyoxymethylene Dimethyl ether, found that the soot concentrations of biodiesel 85% blend is as low as 0.01g/kwh when compared with pure diesel and pure biodiesel. Zunquing etal [3] studied the performance of a RCCI engine with three biofuels n butanol, 2.5 DMF and ethanol being port injected with biodiesel as main fuel. Out of the blends tested, the biodiesel-ethanol blend has the lowest NO\(_x\) and soot emissions when compared to other blends, with 1.5 g/kwh and 0.3 FSN respectively. Najafi [4] blended CNT and Ag nano particles with diesel and biodiesel blends and conducted combustion study on single cylinder diesel engine. They observed that the peak pressure was
increased by 15% with increase in diffusion combustion phase and decrease in combustion duration. Hasan et al [5] conducted experiments in conventional CI engine with tea seed oil biodiesel and diesel blends. The CO is found to decrease with increase in NOx and CO2 emissions. With hydrogen addition to engine, the CO and CO2 emissions were found to decrease. Parvaneh et al [6] studied the comparative performance of three biodiesel castor oil biodiesel, coconut oil biodiesel and waste cooking oil biodiesel blends with pure diesel in proportions of 5%, 10%, 20% and 30% and conducted the study in a turbocharged diesel engine. Results show that performance and emission characteristics of waste cooking oil biodiesel and coconut oil biodiesel are better than others. Qiong et al [7] studied the properties of Tung oil biodiesel. They found that the stability of tung oil biodiesel blend with diesel is better than pure biodiesel. Osman et al [8] conducted the experiments on 7.5 HP, 3600 rpm DI diesel engine with biodiesel, diesel and alcohol blends and observed that at a BMEP of 0.27 MPa the maximum efficiency of 26% with corresponding decrease in CO emissions to 0.25%. Jayashri et al [9] conducted studies with neem biodiesel with diesel blending in various proportions with diesel. They observed that the brake thermal efficiency was higher than that of pure diesel and lower CO and NOx emissions than diesel by 22% and 23% respectively. Bowen et al [10] studied the emission and combustion characteristics of 0.5L diesel engine with polyoxymethylene dimethyl ether with biodiesel blend. They observed that soot and NOx reduction simultaneously to 0.0009 g/kwh and 0.05 g/kwh for 15% polyoxymethylene dimethyl ether with 85% of biodiesel blend. Studies [11] conducted on methyl esters of cashewnut shell oil as engine fuel in a 5.2 kW, 1500 rpm constant speed diesel engine and found that this ester can operate with an efficiency of 25.7% at full load. Karthikeyan et al [12] studied the performance and emission characteristics of grape seed oil methyl ester blends in a 4.4 kW, 1500 rpm diesel engine. The NOx and CO2 emissions of B10, B15 and B20 were lower than that of diesel by 200 ppm. Subhash and Satishchandra [13] trans esterified an suggested Tung oil biodiesel as an alternative fuel to diesel engine. Studies [14] conducted on improvement of grape seed oil with hydrogen addition improved the brake thermal efficiency to 2.06% for energy contribution from hydrogen by 14.46%. The penalty is the increase in NOx emission encouraging reduction in smoke emission. Kalam Azad and Mohammad Razul [15] studied the Grape seed oil blends as fuel in a variable speed diesel engine and observed that 5% blend of grape seed methyl ester and pure diesel can be used as a fuel in diesel engine. Sreedhar and Durgaprasad [16] studied the usage white grape seed oil biodiesel in a 5.2 kW diesel engine and observed that NOx emission of pure biodiesel is 950 ppm and lowest of all blends of this biodiesel and diesel. On Studies [17] conducted on different piston bowl geometries in a diesel engine powered by grape seed oil methyl ester and 100 ppm of zinc oxide nano particles, it was found that toroidal shaped piston bowl improves performance and reduction in NOx emissions (13.2% at full load conditions).

In this study, the methyl esters of Babool oil, Grape seed oil and Tung oil were prepared by transesterification process. The transesterification process is a chemical reaction process between the fatty acids of vegetable oils and methanol. Sodium hydroxide was used as catalyst. One stage trasesterification process was adopted. The methyl esters were washed thoroughly and properties of methyl esters were determined. The performance and emission characteristics of the 3.7 kW engine at constant speed were studied and the characteristics were plotted for various loads.
2. Experimental set up
The experimental set up consists of a 3.7 kW, 1500 rpm constant speed kirloskar engine with electrical loading. The engine runs at a constant speed of 1500 rpm at all loads. The fuel consumption and air consumption were studied using U tube manometers. The loads were applied by varying the electrical resistance to the alternator attached to crank shaft of the engine. The speed of the engine was measured by a non contact type tachometer. The emission measurements were made with Crypton 235 analyser attached to exhaust gas side of the engine. The smoke emissions were measured by Hartridge smoke meter at various loads.

2.1 Test procedure
The tests were conducted with diesel as fuel as referral data. The fuel consumption and air consumptions were measured after the steady state had reached after applying load and ensuring constant rpm of the engine. The HC, CO, CO2 and NOx emissions were measured by introducing the probe into the exhaust pipe of the engine. The smoke was measured by using the Hartridge smoke meter by filter paper method. After the filter paper was strained by the exhaust gas, the smoke intensity was measured by LED set up of the smoke meter. Tests were repeated with other methyl esters.

2.2 Test Fuels and Properties
The properties of fuels to be tested are shown in Table 1. The viscosity of Babool oil methyl ester (BOME) and Grape seed oil methyl ester (GSME) is lesser than many biofuels. Also their high calorific
value qualifies them as a candidate for engine test. Even though, TOME has higher calorific value than diesel, its viscosity and density are high.

| Fuel       | TOME  | BOME  | GSME  | DIESEL |
|------------|-------|-------|-------|--------|
| Calorific Value (kJ/kg) | 44284 | 47218 | 47000 | 42500  |
| Kinematic viscosity (cSt) at 40°C | 9.74  | 4.82  | 4.67  | 2.88   |
| Density (g/cc)      | 0.9084| 0.8810| 0.8864| 0.84   |

3 Results and Discussion

3.1 Performance Characteristics

3.1.1 Brake thermal efficiency.

The variations of brake thermal efficiency with load for the fuels are shown in Figure 1. As load increases, the brake thermal efficiency of all the fuels is increasing. Among the fuels diesel and GSME had their efficiencies very close to each other. At maximum load, the efficiency of diesel is 25.8%, which is slightly higher than GSME whose efficiency is 25% at the same load. Higher density of GSME may hinder the combustion at high load. The TOME had its brake thermal efficiency lower than other two fuels for all loads due to its high viscosity. The oxygen content in the fuel reduces the calorific value of the fuel generally[11]. But in these fuels, the calorific value is found to be higher than that of Diesel. Because of heavier nature of these biodiesels, the vaporization, combustible mixture formation and ignition would have been disturbed. Hence these biodiesels have low brake thermal efficiency than diesel operations.

3.1.2 Volumetric efficiency.

The volumetric efficiency of the CI engine generally decreases with load. This is due to combustion of higher mass of fuel that is injected due to increase in load. The combustion duration remains same in terms of crank angle degree. The increased mass of fuel increases the mass of residual exhaust gas inside the cylinder. Hence induction of volume of fresh air decreases, which decreases the volumetric efficiency of the engine. The volumetric efficiency of all fuels is close to each other. For comparison, the TOME had
the lowest volumetric efficiency of 89.6% where as for diesel it is 92% at full load. Higher volumetric efficiency indicates higher air flow rate of air through the engine, which is very essential for high power output of the engine. High viscosity of TOME decreases the power output due to constrained combustion for the same displacement. Hence lower volumetric and brake thermal efficiency as well for TOME.

Figure 3. Volumetric efficiency versus load

3.2 Emission Characteristics
3.2.1 CO emissions
The variation of CO emission with load for the fuels tested is shown in the Figure 4. The CO emission increases with load for all fuels. The TOME emits 0.1% CO emissions which is the highest among all fuels at full load. Diesel had the lowest CO emissions of 0.07% at full load. CO is formed due to incomplete combustion of fuels in the engine. High viscosity of fuels reduces the ignition and combustion quality of fuel. Due to which, the fuel could not burn fully and incomplete combustion leads to formation of carbon monoxide. High emissions of CO are observed with TOME due to its highest viscosity and density among all. Further, the fuel bound oxygen may promote partial oxidation of carbon during the exhaust process.

3.2.2 CO$_2$ emissions
The variation of CO$_2$ emissions with load for the fuels is shown in the Figure 5. The CO$_2$ emissions are increasing with load. As fuel admitted increases with load, the CO$_2$ emission also increases. CO$_2$ emission is an index of combustion quality of any fuel. Due to superior quality of BOME such as less viscosity, high calorific value, the combustion should be better. This is indicated by the high CO$_2$ emissions of 4.1% for BOME and 4.7% for diesel at full load. TOME had the lowest CO$_2$ emission of 3.3% due to combustion impairment which arises due to heavy nature of oil, at the same load. Generally the number of carbon atoms in the fuel influences the combustion and formation of carbon dioxide. Together with fuel bound oxygen, the combustion improves in GSME as it contains more carbon atoms than its counterparts.
3.2.3 \textit{HC emissions}

The variation of \textit{HC} emission of the engine with load is shown in the Figure 6. \textit{HC} emission of all fuels increases with load for all fuels. \textit{HC} emission is an index of hindered combustion of fuel. TOME had the highest \textit{HC} emission of 140 ppm at full load, where as the diesel and BOME had the \textit{HC} emission of 60 ppm and 120 ppm respectively at the same load. TOME being thicker, the atomization and volatility of the fuel will pose difficulty in combustion. At higher loads, the \textit{HC} emission of BOME is sharply increasing due to its high density. The combustible mixture formation is influenced by nature of fuel and in cylinder conditions. The presence of long chain hydrocarbon may reduce the combustion rate generally.
3.2.4 NOx emissions

The variation of NOx emission with load is shown in the Figure 7. The NOx emission increases with load for all fuels. NOx is an index of attaining in cylinder high temperature during combustion. This is possible for fuels with good combustion qualities. Diesel emits the highest NOx emissions of 1180 ppm at full load. The methyl esters of Grape seed oil, Babool oil and Tung oil emits NOx lower than that of diesel. The NOx emission of GSME is 1100 ppm, BOME is 960 ppm while it is 920 ppm for TOME at full load. As the combustion is inferior due to high density and low volatility, when compared to diesel, the NOx emissions were also less for these methyl esters. The impaired combustion brought low temperature inside the cylinder. The in cylinder high temperature is the primary reason for NOx formation. In spite of fuel bound oxygen, due to difficulty in combustion, NOx formation is lesser.
3.2.5 Smoke emissions

The variation of smoke emission with load is shown in the Figure 8. The smoke emission increases with load for all fuels. The smoke emission is highest for TOME. It is 7.1 FSN for TOME for full load. The smoke emission of diesel and BOME is 5.1 and 6.7 FSN at same load, while GSME emits 5.9 FSN. All methyl esters had smoke emission higher than that of diesel due to the long chain hydrocarbon in the fuel. Generally, the fuel bound oxygen reduces the possibility of high local air fuel ratio and sometimes promotes the oxidation of soot nuclei during combustion. Due to this fact, there is only marginal difference between smoke emissions of diesel and GSME for major loads.

4 Conclusion

The methyl esters of Tung, Grape seed and Babool oils were produced by transesterification process and their properties were tested. On ascertaining the properties, it is found that these methyl esters can be used as engine fuels. The fuels were tested in a 3.7 kW, 1500 rpm constant speed kirloskar engine at various loads. It is found that both methyl esters sustain the engine operation at all loads. GSME is found to have higher thermal efficiency of 25% at full load, next to and closer to diesel engine efficiency of 25.8%. GSME emits 1100 ppm of NOx, which is next to that of diesel NOx emission of 1180 ppm. BOME has low NOx emissions of 960 ppm at full load, considerably lower than that of diesel. The NOx emissions of TOME and BOME were lower by 22% and 27% than that of Diesel fuel. CO2 emissions of GSME are lesser by 17% from diesel’s CO2 emission. The CO2 emissions of these biodiesels were 13% and 29% lower than diesel fuel emissions at full load for BOME and TOME respectively. However the smoke emissions are higher than that of pure diesel operation of the engine. The long term study of applications of these oils may be necessary to learn about engine deposits.

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