Performance and Emission Characteristics of Ternary Fuel Blends in Diesel Engines

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Abstract. The unprecedented use of petroleum fuels in recent years has created an imbalance in the supply and demand. Moreover, fast depletion of these fuels, price perturbation and multi-fold increase in greenhouse gas emissions are debatable issues amongst the scientific fraternity. A sustainable solution to the above problems is to shift towards the renewable alternative fuels. In the Indian context, diesel substitute have special relevance. Ethers have some promising properties similar to diesel, out of which Diethyl ethers (DEE) are most promising alternatives. The present investigation deals with the effect of DEE blends on the performance and emission characteristics of unmodified compression ignition (CI) engines. During the present investigation, ternary blends of diethyl ether, jatropha biodiesel (JB) in diesel were prepared in different proportions. The physico-chemical properties and spray characteristics of the test fuels including density, viscosity, calorific value and Sauter mean diameter (SMD) were also calculated. The experimental results reveal that there is no significant effect of the addition of DEE and JB on the brake thermal efficiency. However, the ternary blend carrying 7.5% of DEE and JB yields the maximum efficiency of 27.9% which is nearly equal to that of peak efficiency of diesel fuel i.e. 28.4%. The exhaust emissions studies reveal that the percentage of CO, HC, NOX and smoke opacity were reduced significantly. Therefore usage of ternary fuel blends of diesel, JB and DEE is a viable approach for the partial replacement of diesel.

1. Introduction
A global crisis of crude oil and increasing threat to the environment due to emissions from prime movers like internal combustion engines have inhibited the attention of researcher fraternity towards the promising domain of alternative transportation fuels. As compression ignition engine has been used as a commercial prime mover in the Indian economy since a number of decades, so, the researchers are adhering to the field of alternative fuels for this stallion of Indian economy. Energy sources and alternative transportation fuels are a concern of utmost significance not only among the scientific and engineering area but also in framing economic and public policy. Elective energizes and vitality sources give a superb chance to presenting an assortment of science points and expanding understudy enthusiasm for those themes. Science and designing fields are progressively disciplinary - exercises on biodiesel can exhibit that unmistakably, by demonstrating the covering of science,
science, and material science in concentrate this and other elective powers. Some of the promising effective alternatives are obtained from biodiesel, alcohols, Di ethyl ether (DEE) [1–7]. These can be used in neat form or with blends.

There are several issues found with biodiesel and vegetable oils in diesel engine [8–10]. However, higher alcohols are gaining limelight for being its greater compatibility in diesel engines. DEE is also a viable alternative because of its lower density and lower viscosity compared to diesel. Moreover, their easy blending and comparable calorific value have made them as a suitable substitute in a diesel engine. Their higher cetane number and higher oxygen content is a very beneficial aspect for its working in a diesel engine. Limited literature is available on the usage of various ternary blends of DEE-diesel-biodiesel in a diesel engine which is an important aspect for this study.

Ali et al. [11] studied the effect of adding DEE (upto 8%) to biodiesel-diesel blended fuel. The authors found better density and acid value with the DEE additive. The authors also observed lower viscosity, cloud point, pour point and calorific value as compared to the blends without DEE.

Ibrahim [12] has experimentally investigated the effect of blending the DEE (upto 15%) with the diesel fuel and found that DEE helped in better engine performance for most of the engine loadings.

Ashok [13] added DEE in the diesel-ethanol emulsion. The author found better performance, combustion and emission of a diesel engine owing to higher cetane number of DEE. Brake thermal efficiency (BTE) of the blends was also found to be comparable to diesel.

Roy et al. [14] used biodiesel-diesel-DEE blends and found lower carbon monoxide (CO) and hydrocarbon (HC) emissions and comparable nitric oxide (NO) and nitrogen dioxide (NO₂) emissions.

Lee et al. [15] has used DEE with diesel and found that the combustion of DEE blended fuels produced lower particulate matter (PM), CO and HC emissions than diesel due to the high oxygen content of DEE. The authors also found a bit higher oxides of nitrogen (NOₓ) from the blended fuels.

Tudu et al. [16] studied the effect of DEE in tyre pyrolysis oil-diesel blends. The authors found that the addition of DEE helped in lowering the CO, carbon dioxide (CO₂), HC and smoke emissions with some penalty on NOₓ emissions.

Rakopoulos et al. [17] conducted experiments on a diesel engine using blends of diesel fuel with ethanol, butanol and diethyl ether at different volume percentages for emission analysis. The authors found that by increasing the percentage of all biofuels in the blends, a significant reduction of smoke opacity (mainly higher for butanol blend), a reduction of NOₓ emissions (mainly higher for DEE blends), as well as a reduction of CO emissions compared to diesel fuel.

Venu et al. [18] used (alcohol-biodiesel-diesel) with DEE as ignition enhancer. The authors found that the test fuels results in better engine performance with minimal emissions. The authors also concluded that the fuel blends can be used directly in the engine as a potential alternative for diesel fuel without any modifications.

Based on the literature it is found that the usage of ternary fuel blends of diesel, biodiesel and DEE is not completely explored. In this study, usage of different blends of diesel, jatropha biodiesel and DEE were formulated. Several physico-chemical properties of the blends were determined. Emission and performance characteristics were determined for analyzing the usage of the blends in a diesel engine.

### 2. Material and Methods

Jatropha biodiesel (JB) is prepared from the potassium hydroxide, methanol, sulphuric acid (analytical grade) purchased from the local vendor in New Delhi. Jatropha seeds were collected from the campus of DTU and the oil was extracted from the seeds with the help of an expeller. The free fatty acid content of the oil was 5.8%. It is converted to biodiesel using two-step transesterification process discussed in [19–21]. Table 1 describes the nomenclature of the test fuels.
Table 1. Nomenclature of the test fuels

| S.NO. | BLENDS   | DEE (% v/v) | BIODIESEL (% v/v) | DIESEL (% v/v) |
|-------|----------|-------------|--------------------|----------------|
| 1     | D100     | 0           | 0                  | 100            |
| 2     | DEE2.5B  | 2.5         | 2.5                | 95             |
| 3     | DEE5B5   | 5.0         | 5.0                | 90             |
| 4     | DEE7.5B  | 7.5         | 7.5                | 85             |
| 5     | DEE10B1  | 10          | 10                 | 80             |

Figure 1. Test samples

Table 2 describes the equipment’s used for determining density, kinematic viscosity calorific value, and Sauter mean diameter of the fuels.

Table 2. Equipment’s used for determining different properties

| Property                  | Equipment                   |
|----------------------------|-----------------------------|
| Density                   | Anton Parr DMA 4500         |
| Kinematic Viscosity       | Capillary tube              |
| Calorific Value           | Parr 6100 Oxygen Bomb Calorimeter |
| Sauter Mean Diameter      | Malvern Spraytec            |

Table 3 shows the properties of the test fuels determined using the equipment.

Table 3. Properties of the test fuels

| BLENDS       | Density (g/cm³) | Kinematic viscosity (cSt) | Calorific Value (MJ/Kg) | Sauter Mean diameter (µm) |
|--------------|-----------------|---------------------------|-------------------------|--------------------------|
| DEE2.5B2.5   | 0.82456         | 2.65                      | 42.57                   | 21.1                     |
| DEE5B5       | 0.8235          | 2.82                      | 41.94                   | 21.7                     |
| DEE7.5B7.5   | 0.82444         | 2.99                      | 41.72                   | 22.2                     |
| DEE10B10     | 0.82667         | 3.14                      | 40.64                   | 22.9                     |
| D100         | 0.825           | 2.6                       | 44.50                   | 20.8                     |
Figure 2. Setup of diesel engine test rig

Table 4 gives about the typical specification of the diesel engine used for the testing. The engine used was a Kirloskar make unmodified air cooled diesel engine.

Table 4. Specifications of the diesel engine

| Make       | Kirloskar            |
|------------|----------------------|
| Model      | DAF8                 |
| Type       | Single cylinder, vertical. DI diesel engine |
| Speed      | 1500 rpm, constant speed |
| Bore (mm)  | 95                   |
| Stroke (mm)| 110                  |
| Compression Ratio | 17.5            |
| Cooling System | Air cooled        |
| Cycle      | 4 stroke             |
| Maximum output power (KW/HP) | 5.9/8.0  |

All the tests were performed on the developed test rig at varying loads. The results were taken thrice and an average of the three was taken for the better accuracy of the results. Emission tests were carried on AVL Digas analyzer and AVL smoke meter.

3. Performance characteristics

3.1. Brake Thermal Efficiency
From Figure 3 the brake thermal efficiency with BMEP variation at different loading conditions is seen. The efficiency shows an increasing trend to near about 60% load and decreases afterward. BTE decreases sharply after 80% load.
Maximum efficiency of 28.4% is witnessed with 100% diesel at about 60% load and for blends in which diesel is replaced by DEE and Jatropha biodiesel shows a maximum efficiency of 27.9% with the DEE7.5B7.5 blend. The blend that resulted in most inferior efficiency is for DEE2.5B2.5. In overall prospect, the performance of the engine in terms of BTE is quite comparable to that with diesel, no significant hampering to engine performance is witnessed with ternary blends of DEE and biodiesel in diesel. The most superior fuel among the blends was DEE7.5B7.5 giving highest efficiency among all blends because of its comparable viscosity and energy content. Moreover, added oxygen from DEE and JB is helping in better combustion. DEE10B10 is having slightly lower BTE because of higher viscosity, lower energy content and less Sauter mean diameter (SMD) than DEE7.5B7.5. All other test fuels have lower BTE owing to the lower oxygen content of the fuels. DEE also has higher cetane number which also promotes better combustion and hence shall help in achieving better BTE. SMD of the blends were comparable to diesel which exhibits similar spray characteristics and helps in promoting combustion.

![Figure 3. BTE vs BMEP](image)

3.2. Brake Specific Energy Consumption

From Figure 4 the brake specific energy consumption (BSEC) variation at different loading conditions is seen. BSEC in general for all blends and diesel as well decreases sharply with increasing load. Maximum BSEC is observed for DEE2.5B2.5 because of lowest BTE among all prepared test fuels. It is observed that on adding DEE and JB to diesel, the BSEC values decrease. However, for DEE10JB10, owing to low energy content and high viscosity, BSEC is lower as compared to DEE7.5B7.5. Calorific value of DEE and JB is quite lower as compared to petroleum diesel. It therefore needs more energy input for producing the same efficiency. Therefore, BSEC of the blends are higher as compared to diesel fuel.
4. Emission Characteristics

4.1. Exhaust Gas Temperature
From Figure 5 the exhaust gas temperature variation at different loading conditions is plotted against BMEP. Exhaust temperature shows an increasing trend with the load. Maximum exhaust temperature reached is with diesel fuel i.e. 332°C at full load. For the blends, DEE2.5B2.5 shows a maximum exhaust temperature. Greater the percentage of DEE in the blends lower is the exhaust gas temperature. DEE helps in lowering the temperature of the blends due to quenching effect produced in the cylinder. Diesel shows overall higher exhaust temperature as compared to ternary blends for respective loads and BMEP.

4.2. CO Emissions
From Figure 6 shows the CO emissions variation at different loading conditions is plotted against BMEP. CO emissions are steady till 60% load conditions after 60% load CO emissions rises sharply. CO emissions for diesel fuel is highest because of the absence of oxygen. The ternary fuel blends prepared were having lower CO emissions owing to the presence of oxygenated compounds. Moreover, better combustion of the ternary fuel blends was observed. It can be because of the addition of DEE and JB which have better cetane number than diesel which shall exhibit better combustion and therefore lower CO emissions. However, DEE10B10 has slightly higher CO emissions then DEE7.5B7.5 because of its higher viscosity, lower heating values and higher SMD of the DEE10B10 blend as compared to DEE7.5B7.5.
4.3. \textit{HC Emissions}

From Figure 7 the HC emission variation at different loading conditions is plotted against BMEP. HC emissions increase as the load increases for all the fuel taken into consideration for engine trials. DEE2.5B2.5 shows lower HC emission characteristics at part load up to 40% load, after that emissions increases sharply. HC emission for DEE10B10 is higher at all loads as compared to other blends. Owing to lower energy content, higher viscosity and higher SMD of DEE10B10 blend, more HC emissions were liberated in the atmosphere. However, HC emissions of diesel fuel are higher than the blends carrying DEE 7.5\% or lower because of complete combustion of the blends and more prolonged effect of biodiesel in them.

4.4. \textit{NO}_{X} Emissions

From Figure 8 the NO\textsubscript{X} emissions variation at different loading conditions is plotted against BMEP. NO\textsubscript{X} emissions for diesel and DEE2.5B2.5 are quite comparable and are on the higher side in comparison to other blends. DEE5B5, DEE7.5B7.5 and DEE10B10 shows lower NO\textsubscript{X} emissions. The reason for lower NO\textsubscript{X} can be attributed to the greater quantity of DEE in the blends which leads to more quenching effect in the cylinder. Also NO\textsubscript{X} depends on the exhaust gas temperature of the engine. Lower the exhaust gas temperature, lower is the NO\textsubscript{X}. Therefore DEE helps in cooling the cylinder and lowering the temperature which results in lower thermal NO\textsubscript{X}. 
From figure 9 the smoke opacity emissions variation at different loading conditions is plotted against BMEP. Smoke opacity is nearly the same for all fuels tested, however, usage of biodiesel and DEE both having more oxygen content and more cetane number leads to proper burning and hence produces lower smoke emissions. Therefore DEE2.5B2.5 and DEE5B5 produce lower smoke emissions than diesel. It is also found that DEE7.5B7.5 produces the lowest smoke because of better burning then DEE10B10 owing to lower viscosity and smaller SMD of DEE7.5B7.5 which leads to proper atomisation of the fuel and produces less smoke when compared to diesel.

5. Conclusions
The current study focused on using ternary fuel blends of diesel, JB and DEE in varying proportions. The results have shown comparable physico-chemical properties and SMD. An unmodified diesel engine is used for determining the performance and emission characteristics. BTE and BSEC of the test fuels were very similar to diesel which shows that the addition of DEE in diesel and biodiesel gives comparable BTE and BSEC. However, the ternary blend carrying 7.5% of DEE and JB yields the maximum efficiency of 27.9% which is nearly equal to that of peak efficiency of diesel fuel i.e. 28.4%. Slight lower CO, HC, NOX and smoke opacity emissions were observed for the blends. However, for DEE10B10 blend, HC emissions were somewhat higher owing to lower energy content, higher viscosity and higher SMD of DEE10B10 blend. The current study has revealed that the ternary blends of diesel, biodiesel and DEE shall be a viable solution for the replacement of diesel because of favorable results.
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