Comparative studies of a bioethanol fuelled DI diesel engine with a cetane improver

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Abstract: Flowers of madhuca indica tree are found to be a potential source for bioethanol production. The present work is aimed to study the effect of diethyl ether (DEE) as a cetane improver on engine behaviour when the DEE is added to bioethanol diesel emulsion in little quantities and used as fuels. 1% and 2% of DEE were added on a volume basis to BDE15 (bioethanol-diesel emulsion up to 15%) and named as BDED1% and BDED2% respectively. The combustion, performance and emission results were compared with those of diesel operation. The results showed that the bioethanol diesel emulsion operation, with and without the cetane improver, showed a higher brake specific energy consumption and exhaust gas temperature than that of diesel operation at maximum brake power. There was a simultaneous reduction of brake specific nitric oxide (BSNO) and smoke emission with the addition of cetane improver in bioethanol diesel emulsion. [Received: February 4 2014; Accepted: September 20 2014]

Keywords: diesel; madhuca indica flower; bioethanol diesel emulsion; DEE; diethyl ether.

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1 Introduction

Air pollution is one of the major issues faced by the world today, which contributes to climate change, low rain fall, drought etc. Automotive vehicle is one of the major sources of air pollution. So, importance is given to reduce the pollutants from the automobile vehicles. This can be possible by finding new alternative fuel processing methods to improve the fuel quality or a new alternative fuel or develop engine technologies. A recent report by the International Energy Agency (IEA) has highlighted that biofuels have a great potential in reducing transport related CO₂ emissions by 50% by 2050 (IEA, 2011). Biofuels such as ethanol and biodiesel play a prominent role in energy security, and less emission formation in internal combustion engines. The Environmental Protection Agency (EPA) has adopted the ‘Go green technology’ for reducing the green house gases. It suggested two methods for implementing ‘Go green technology’, which are

1. improving energy efficiency
2. use of renewable energy.

It also emphasises to use more ethanol/bioethanol in transportation. In practice, when two different gasoline and ethanol fuel blends are dispensed from the same hole and nozzle, residual fuel from a prior fuelling of gasoline ethanol blend may mix with a subsequent fuel blend and affect fuel supply system. The EPA has recently suggested to use a blender pump which is also known as a multiple grade dispenser used to dispense multiple gasoline and ethanol blended fuels through a common hole and nozzle (King, 2014; EPA, 2014; Beer and Grant, 2007). Bioethanol can be produced from simple sugar such as sugar cane, sugar beet, molasses, or from other carbohydrates that can be converted to sugar, such as starch and cellulose. Examples of starch feed stocks are corn, maize, potatoes etc. and examples of cellulosic material are wood, forest residue, agricultural residue, crop residue, etc. (Demirbas, 2012). Bioethanol produced from food grains and sugar-based vegetables like sugar beet restrict the use of bioethanol production in a large quantity in developing countries, because it results in food crisis. Therefore, researchers started to find appropriate methods to derive bioethanol from different feed stocks such as forest residue, wood residue, stem of plant etc (Quintero et al., 2008; Almodares and Hadi, 2009; He et al., 2009; Mays et al., 1990; Dodic et al., 2009; Rani et al., 2010; Dewi and Trisunaryanti, 2011; Ming and Dale, 2008; Torget and Hsu, 1994; Torget et al., 1990, 1991; Sun and Cheng, 2005; Triana et al., 2011; Ge et al., 2011).

The direct use of bioethanol with diesel is difficult, because of its lower cetane number and poor miscibility with diesel. Also, bioethanol exhibits a longer ignition delay than that of diesel when it is used as a fuel, because of its poor cetane quality. To overcome this issue, fuel modification is required. Nitrate-based cetane improvers such as triethylene glycol dinitrate (TEGDN), octyl nitrate, isoamyl nitrite were added to ethanol in lower quantities and investigation were carried out with the mixture effect on combustion, performance and emissions of a CI engine at different parameters and geometry by many researchers (Ren et al., 2008; Holland et al., 1992; Hadenberg and Schaefer, 1981, Hadenberg and Schaefer, 1981; Simonsen and Chomiak, 1995). Some of researchers reported that there was a drop in power while few have reported the similar results to that of diesel. It was also reported that the NO, CO and smoke emissions were found to be decreased while the HC emission was increased (Holland et al., 1992).
Polyethylene glycol with the trade name BERAID and glycerol ethoxylate were used to replace the nitrate-based improver with various contents and observed that there was an increase in efficiency and the rate of pressure rise (Simonsen and Chomiak, 1995; Munsin et al., 2012). Oxygenate-based cetane improvers such as DME, DEE were also investigated as cetane improvers with bioethanol. On combustion point of view, the ignition delay was found to be shortened and the peak pressure reduced in CI engines. The oxides of nitrogen and smoke emissions were found to be reduced (Cipolat and Bhana, 2009; Ashok and Saravanan, 2007).

Experimental studies were conducted earlier with three different emulsions namely, BDE5, BDE10 and BDE15, where the number denotes the percentage of bioethanol in the emulsion. For example, BDE10 refers to 10% bioethanol, 1% surfactant and 89% diesel on a volume basis. All the emulsions were tested as fuels in a single cylinder, four stroke, air cooled, DI diesel engine, developing a power of 4.4 kW at a rated speed of 1,500 rpm. The combustion, performance and emission parameters of the engine were evaluated and compared with those of diesel operation. The results indicated that BDE15 gave better performance, lower emissions, and combustion parameters comparable to that of diesel operation. However, the ignition delay was found to be longer and rate of pressure rise was also found to be higher for the emulsions than that of diesel. In order to reduce the ignition delay and to improve the performance of the engine, 1% and 2% of DEE was added to the emulsified fuel. The engine combustion, performance and emission behaviour were studied, compared with those of diesel and BDE15 and presented in this paper.

2 Materials and methods

The feedstock used in this study is madhuca indica flower, which was collected from the madhuca indica tree. It is a forest tree grown abundantly in the tropical regions of Asia and Australia. The residues from the tree are used for different purposes, such as cattle feed and biomass used in direct combustion. The annual production of madhuca indica flowers in India in the year 2006 was estimated to be approximately 48,000 M Tonnes (Mohanty et al., 2009; Swain et al., 2007). The fresh madhuca indica flowers can be used as a source of bioethanol production. The tribal people from different locations in India and Pakistan produce country liquor by the fermentation process. Mohanty et al. (2009) established the production method for bioethanol from the madhuca indica flowers by solid state fermentation. They studied various factors, such as the moisture content, initial pH and temperature, affecting bioethanol production. Figure 1 shows the schematic diagram of the bioethanol production process.

For this study, bioethanol was produced from madhuca indica flowers by the fermentation process, using Saccharomyces cerevisiae. The fresh flowers of madhuca indica were collected from the village people, cleaned properly to remove the adhering soil particles, and dried in the sun. The yeast (Saccharomyces cerevisiae) was cultured on yeast extract nutrient broth (YENB) having 5% glucose and 1% of yeast extract for 48 hours. The madhuca indica flowers were pre-treated for the extraction of sugars. The flowers of madhuca indica and distilled water in a 2:1 ratio were autoclaved, at a pressure of 68.9 kPa for 15 minutes. For the fermentation process, a starter culture was added at the rate of 10% (v/v) to the madhuca indica extract taken in a 1,000 ml Erlenmeyer flask,
and fermentation was carried out in a batch on laboratory bench at a temperature of 30°C ± 2 C for 96 hours. After the fermentation process, the first distillation was done to get the crude extract and further, fractional distillation was done for the removal of water. The purity of bioethanol was checked by an alcoholmeter. The emulsions of 15% of bioethanol, 84% of diesel and 1 and 2% of DEE were prepared with the addition of a surfactant span 80 at 1% on volume basis. The surfactant was used to reduce the oil and water surface tension, to make micro emulsions by maximising the surface area. Span 80 has a hydrophilic lipophilic balance (HLB) number of 4.3 and, it is more lipophilic than hydrophilic which is an appropriate surfactant for water-in-oil-emulsion (Qi et al., 2010). The resultant mixture was stirred vigorously with the help of a mechanical agitator at the rate of 1,800 to 2,000 rpm for about 30 minutes. The emulsions were kept under an observation for 20 days to check the miscibility. There was no separation found in the emulsion.

Figure 1 Production process of bioethanol from feed stock (see online version for colours)

3 Properties of tested fuels

Table 1 gives the comparison of the physical properties of bioethanol produced from different feed stocks. The physical properties of bioethanol produced from the madhuca indica flower and BDE15 were tested in a standard fuel testing laboratory, i.e., ITA lab, Kolkata. The physical properties of span 80 are shown in Table 2. The physical properties of DEE are given in Table 3. The properties of BDE15, BDED1%, BDED2% are compared with diesel and given in Table 4.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Bioethanol from sugar molasses</th>
<th>Commercial ethanol</th>
<th>Bioethanol from madhuca indica flower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m3)</td>
<td>790</td>
<td>780</td>
<td>800</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>26.4</td>
<td>26.8</td>
<td>29.4</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>13</td>
<td>22</td>
<td>29</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>-</td>
<td>-117.3</td>
<td>-103</td>
</tr>
<tr>
<td>Kinematic viscosity at 40°C (cSt)</td>
<td>1.3</td>
<td>1.35</td>
<td>1.73</td>
</tr>
</tbody>
</table>
Table 2  Properties of Span80.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>0.995–1.05</td>
</tr>
<tr>
<td>Saponification value (mgKOH/g)</td>
<td>140–160</td>
</tr>
<tr>
<td>HLB no.</td>
<td>4.3</td>
</tr>
<tr>
<td>Hydroxyl value (mgKOH/g)</td>
<td>190–220</td>
</tr>
<tr>
<td>Acid no. (mgKOH/g)</td>
<td>8</td>
</tr>
<tr>
<td>Iodine value (mg iodine/g)</td>
<td>60–75</td>
</tr>
</tbody>
</table>

Table 3  Properties of DEE

<table>
<thead>
<tr>
<th>Properties</th>
<th>DEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>713</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>33.89</td>
</tr>
<tr>
<td>Cetane number</td>
<td>&gt;125</td>
</tr>
<tr>
<td>Kinematic viscosity at 40°C (cSt)</td>
<td>0.194</td>
</tr>
<tr>
<td>Auto-ignition temperature (°C)</td>
<td>160</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>34.4</td>
</tr>
</tbody>
</table>

Table 4  Comparison of properties of BDE15, BDED1% and BDED2% with diesel

<table>
<thead>
<tr>
<th>Properties</th>
<th>Diesel</th>
<th>BDE15</th>
<th>BDED1%</th>
<th>BDED2%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>870</td>
<td>849</td>
<td>835</td>
<td>821</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>42.8</td>
<td>35.34</td>
<td>34.23</td>
<td>32.93</td>
</tr>
<tr>
<td>Cetane number</td>
<td>50–55</td>
<td>5–15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kinematic viscosity at 40°C (cSt)</td>
<td>2.58</td>
<td>1.95</td>
<td>1.5</td>
<td>1.23</td>
</tr>
<tr>
<td>Auto-ignition temperature (°C)</td>
<td>210</td>
<td>280</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4  Experimental set up

Experiments were conducted in a single cylinder, four strokes, air cooled, direct injection diesel engine developing a maximum power output of 4.4 kW at constant speed of 1,500 rpm. The schematic diagram and specifications of test engine is given in Figure 2 and Table 5 respectively. An anti-pulsating drum is fixed with the intake manifold of the engine which maintains a constant suction pressure, avoid the fluctuation in the load and also it facilitate the constant air flow through the orifice metre. The orifice metre measures the volume of air drawn into the cylinder with the help of a U tube manometer. Fuel consumption of the engine at different load is measured with the help of burette and optical sensor.
Figure 2  Schematic diagram of experimental set up

Notes: 1 Engine  
2 Flywheel  
3 Air box  
4 Manometer  
5A Fuel tank for diesel  
5B Fuel tank for emulsion  
6 Burette  
7 Speed sensor  
8 Alternator  
9 Load cell  
10 Fuel injector  
11 Pressure transducer  
12 Control panel board  
13 Data acquisition card  
14 Personal computer  
15 AVL437C smoke metre  
16 AVL Digas 444 analyser

Table 5  Technical specifications of diesel engine

<table>
<thead>
<tr>
<th>Type</th>
<th>Kirloskar TAF1 Vertical diesel engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cylinder</td>
<td>1</td>
</tr>
<tr>
<td>Type of injection</td>
<td>Direct</td>
</tr>
<tr>
<td>Rated power at 1500 rpm, kW</td>
<td>4.41</td>
</tr>
<tr>
<td>Bore, mm</td>
<td>87.5</td>
</tr>
<tr>
<td>Stroke, mm</td>
<td>110</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17.5</td>
</tr>
<tr>
<td>Method of cooling</td>
<td>Air cooled with radial fan</td>
</tr>
<tr>
<td>Displacement volume, litres</td>
<td>0.662</td>
</tr>
<tr>
<td>Fuel injection timing BTDC, degree</td>
<td>23°</td>
</tr>
<tr>
<td>Number of injector nozzle holes</td>
<td>3</td>
</tr>
<tr>
<td>Nozzle-hole diameter, mm</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Two fuel tanks are used in the study, where fuel tank A stores diesel while tank B stores bioethanol emulsion. Two valves are fitted in the fuel line from A and B to allow or stop the fuel flow from two different tanks. A burette is fitted with two optical sensors at high level and low level of both the ends. Fuel is drawn from 6 litre capacity fuel tank to the burette under gravity. When fuel passes through an optical sensor, it sends signal to the computer for automatic start/stop of time required for fixed amount of fuel supply i.e., 20 cc to measure the fuel consumption and again the burette is refilled automatically for next measurement. A non-contact type PNP sensor gives a pulse output for each revolution of the crank shaft for measurement of engine speed. Engine is coupled with an alternator through a load cell bank for loading purpose.

A K-type (Cr Al) thermocouple connected in the exhaust pipe measures the exhaust gas temperature (EGT) with temperature range of 0–900°C. The cylinder pressure measurement at a particular crank angle is measured with the help of a Kistler made quartz piezoelectric pressure transducer (Model Type 5395A), mounted on the cylinder head in the standard position. The piezoelectric pressure sensor is in line with charge amplifier which converts electric charge generated in a piezoelectric pressure sensor to voltages and input into conventional measurement in a data recorder. A crank angle encoder 365C is fitted to the end of the engine shaft to measure the angular position of the crankshafts. All the data measured by sensors are processed, analysed and displayed with the help of data acquisition system (DAS). The pressure transducer and crank angle encoder will record the pressure and crank angle values. With the help of pressure values obtained for every crank angle degree (CAD), the remaining parameters like ignition delay, heat release rate (HRR), combustion duration are calculated with the help of a software and stored in an excel sheet. At the exhaust of the engine, an AVL DiGas 444 analyser probe is inserted and kept for a few minutes for the measurement of unburnt hydrocarbon (HC) in ppm, carbon monoxide (CO) in vol%, nitric oxide (NO) in ppm. The HC and CO, carbon dioxide (CO2) are measured with the help of the gas analyser that works on the non-dispersive infrared (NDIR) principle. The nitric oxide (NO) emission is measured by a photochemical sensor. The thermostatically controlled diesel smoke metre of model number AVL437C is used to measure the smoke in percentage opacity. The results obtained from measurements are fully compatible with Hatridge smoke units (HSU).

4.1 Experimental procedure

Initially, the engine was operated with diesel fuel to obtain the reference data at different loads ranging from 0–100% for one hour to complete one set of measurement. While changing of the load, the engine was allowed to attain a constant speed of 1,500 rpm to avoid the variable speed due to sudden change of load. It was done with regular check of engine speed with the help of tachometer at the end of timing gear shaft. Later experiments were conducted with BDE15, BDED1% and BDED2% by opening valve B and closing valve A. In every set of experiment, for every load condition, the emission readings were taken three. Then the average value of emission measurements was considered for analysis. The engine was allowed to run with diesel in between the bioethanol diesel emulsions, to eliminate the cumulative effects. Finally, the engine was allowed to run with diesel to flush out the bioethanol diesel emulsions in the fuel line. The engine was able to produce the designed power.
Uncertainty in the experiment and instrument

The uncertainty or margin of error of a measurement is stated by giving a range of values likely to enclose the true value. It is a measure of the goodness of the result. The estimated standard uncertainty \([U \text{ or } U(Y)]\) of the mean is calculated by using the following formula (Stephanie, 1999):

\[
U \text{ or } U(Y) = \frac{s}{\sqrt{n}}
\]

where \(n\) is the number of measurements in the set. The standard deviation \((s)\) for a series of \(n\) measurements can be expressed mathematically as:

\[
s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n-1}}
\]

where \(x_i\) is the result of the \(i^{th}\) measurement and \(\overline{x}\) is the arithmetic mean of the \(n\) results.

By using this equation the standard uncertainty for brake specific carbon monoxide (BSCO), brake specific hydrocarbon (BSHC) and brake specific nitric oxide (BSNO) of diesel, BDE15, BDED1\% and BDED2\% at full load are given in Appendix.

Evaluations of some unknown uncertainties from known physical quantities were obtained using the following general equation.

\[
\frac{U_Y}{Y} = \left[ \sum_{i=1}^{n} \left( \frac{1}{Y \frac{\partial Y}{\partial x_i}} U_{x_i} \right)^2 \right]^{1/2}
\]

In the equation cited, \(Y\) is the physical parameter that is dependent on the parameters, \(x_i\). The symbol \(U_Y\) denotes the uncertainty in \(Y\). By using the above equation the uncertainty of the experiment was obtained as \(\pm 2.57\%\). Table 6 shows the uncertainties of the instrument used in the experiment.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Range</th>
<th>Accuracy</th>
<th>Percentage uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load indicator, W</td>
<td>250–6000</td>
<td>±10</td>
<td>0.2</td>
</tr>
<tr>
<td>Temperature indicator, °C</td>
<td>0–900</td>
<td>±1</td>
<td>0.15</td>
</tr>
<tr>
<td>Speed sensor, rpm</td>
<td>0–10000</td>
<td>±10</td>
<td>1</td>
</tr>
<tr>
<td>Burette, cc</td>
<td>1–30</td>
<td>±0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Exhaust gas analyser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO, ppm</td>
<td>0–5000</td>
<td>±50</td>
<td>1</td>
</tr>
<tr>
<td>HC, ppm</td>
<td>0–20000</td>
<td>±10</td>
<td>0.5</td>
</tr>
<tr>
<td>CO, %</td>
<td>0–10</td>
<td>±0.03</td>
<td>1</td>
</tr>
<tr>
<td>Smoke metre, %</td>
<td>0–100</td>
<td>±1</td>
<td>1</td>
</tr>
<tr>
<td>Pressure transducer, bar</td>
<td>0–110</td>
<td>±1</td>
<td>0.15</td>
</tr>
<tr>
<td>Crank angle encoder, °CA</td>
<td></td>
<td>±1</td>
<td>0.2</td>
</tr>
</tbody>
</table>
6 Results and discussion

6.1 Combustion parameters

6.1.1 Pressure crank angle diagram

The variation of cylinder pressure with crank angle for BDE15, BDED1% and BDED2% with diesel are illustrated in Figure 3. The cylinder peak pressures for BDE15, BDED1% and BDED2% are 77.3 bar, 75.3 bar and 72.8 bar respectively, which is attained approximately at 371.2 °CA, 370.8 °CA and 369.9 °CA respectively at maximum brake power, whereas for diesel, it is 73.4 bar at 369.5 °CA. For the BDE15 emulsion, the combustion pressure occurred approximately at about 2 °CA after diesel. BDE15 attains a maximum cylinder pressure followed by BDED1%, diesel and BDED2%. With the addition of DEE, the ignition delay is shortened. BDE15 shows a higher cylinder peak compared to that of diesel and BDED2% at maximum brake power.

Figure 3  Variation of cylinder pressure with crank angle

6.1.2 Ignition delay

The variation of the ignition delay for diesel, BDE15, BDED1% and BDED2% at different brake power values is shown in Figure 4.

The ignition delay is nothing but the time lag between the start of fuel injection and the start of fuel ignition which is measured in degree crank angle. It was computed by calculating the change in slope of the pressure crank angle diagram, and from a heat release analysis of the pressure crank angle data (Heywood, 2003). The ignition delay of all the tested fuels in this study decreases with an increase in the brake power, as a result of increased cylinder gas temperature. It is also apparent from the figure, that the ignition delay for BDE15 is longer than that of diesel operation throughout the brake power. For BDED1% and BDED2%, the ignition delay is found to be shorter compared to that of diesel. The shorter ignition delay is due to the higher cetane number achieved
by the addition of DEE, compared to that of BDE15 at brake power. The premixed combustion gradually shortened with the increase in the cetane improver volume, in the bioethanol-diesel emulsion (Cai et al., 2004). With the higher percentage of DEE, the cylinder peak is decreased due to high latent heat of vaporisation. The ignition delay for BDED1%, BDED2%, BDE15 varies from 1 to 2 °CA at maximum brake power, compared to that of diesel.

**Figure 4** Variation of ignition delay with brake power

6.1.3 Heat release rate

The heat release analysis can provide information about the effects of engine design changes, fuel injection system, fuel type, and engine operating conditions, on the combustion process and engine performance. The HRR was calculated, using the first law analysis of thermodynamics. The HRR at each crank angle was determined by the following formula:

$$\frac{\partial E}{\partial \theta} = \frac{\partial P}{\partial \theta}(\gamma/\gamma - 1) + \frac{\partial \theta}{\gamma/\gamma - 1}$$

where

- $\partial$ gas volume (m$^3$)
- $\theta$ crank angle (°)
- $\gamma$ ratio of specific heat
- $\frac{\partial E_w}{\partial \theta}$ rate of heat transfer from the wall (J/°CA).

Figure 5 illustrates the variation of HRR with the crank angle for diesel, BDE15, BDED1% and BDED2% at maximum brake power. It is evident from the figure that the HRR is the highest for BDE15 followed by BDED1%, diesel and BDED2%. The higher HRR exhibited by the BDE15 is mainly due to the longer ignition delay than that of...
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It may also be due to better mixing and complete combustion of the fuel air mixture.

**Figure 5** Variation of HRR with crank angle

![Graph showing variation of HRR with crank angle](image)

But, for BDED2%, the HRR is lesser than that of diesel at maximum brake power, due to leaner mixture obtain by the shorter ignition delay.

6.1.4 Peak cylinder pressure

Figure 6 portrays the variation of peak cylinder pressure with brake power for diesel, BDE15, BDED1% and BDED2%. The cylinder peak pressure of a compression ignition (CI) engine is mainly due to the amount of fuel accumulated in the delay period and the combustion rate in the initial stages of premixed combustion.

**Figure 6** Variation of peak cylinder pressure with brake power

![Graph showing variation of peak cylinder pressure with brake power](image)

The peak cylinder pressure for BDE15 is found to be higher than that of diesel operation, which is due to a longer ignition delay at maximum brake power. Due to the accumulation of more fuel and better combustion increases the cylinder pressure. The
cylinder peak pressure for diesel varies from 53.3 bar to 73.4 bar from minimum brake power to maximum brake power respectively. For BDE15 the values of the maximum cylinder pressure from minimum brake power to maximum brake power are 54.3 to 77.3 bar respectively. In the case of BDED1% and BDED2%, the peak pressures are found to be in the range between 62.9 to 75.3 bar and 60.8 to 72.8 bar respectively, from minimum brake power to maximum brake power respectively. The percentage increase of the cylinder peak pressure of BDE15 and BDED1% are 5.3 and 2.5 % respectively, compared to that of diesel at maximum brake power. For BDED2%, the cylinder peak pressure decreases by about 1.8% compared to that of diesel at maximum brake power. This may be due to the shorter ignition delay, which allows lesser accumulation of fuel, and hence, a lower peak pressure is noticed.

6.1.5 Combustion duration

Figure 7 shows the variation of combustion duration for DEE addition, BDE15 and diesel at different brake power. Combustion duration was calculated from the cumulative heat release data computed from the HRR and the duration of 90% of heat release is taken as the combustion duration.

Figure 7  Variation of combustion duration with brake power

The combustion duration increases with an increase in the percentage of DEE addition. But the combustion duration for BDE15 is found to be lesser than that of diesel. The reason is that the addition of bioethanol with diesel decreases the heating value of the emulsion. On the other hand, the oxygenated fuel can promote the combustion rate, and especially the diffusive combustion rate. It can also be observed from the figure that the combustion duration of BDED1% and BDED2% is found to be higher compared to that of diesel at maximum brake power.

6.1.6 Mass fraction burned

The energy conversion during a combustion cycle can be described by the mass fraction burned (MFB) at a specific CAD. In an IC engine, the MFB depends on the engine geometry, engine speed, A/F, ignition angle, residual mass etc. The MFB in each
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individual engine cycle is a normalised quantity with a scale of 0 to 1, describing the process of chemical energy release as a function of the crank angle. The MFB includes the determination of the start and end of combustion (Mendera et al., 2002). One well-established method was developed by Rassweiler and Withrow for estimating the MFB profile from the cylinder pressure and volume data. In this method, the MFB is given by:

\[
MFB = \frac{m_b(i)}{m_b(total)} = \frac{\sum_{0}^{N} \Delta P_c}{\sum_{0}^{N} \Delta P_c}
\]

where

0 denotes the start of combustion

\(N\) end of combustion (\(N\) is the total number of crank intervals)

\(\Delta P_c\) pressure rise due to combustion

\(i\) integer crank angle location.

The MFB is the ratio of the cumulative heat release to the total heat release. Figure 8 depicts the variation of the MFB with the crank angle at maximum brake power.

**Figure 8** Variation of MFB with degree crank angle

It is apparent from the figure that the estimated end of combustion (EEOC) for diesel, BDE15, BDED1\% and BDED2\% is achieved at 400, 398.1, 412.3 and 425.5 °CA respectively at maximum brake power. BDE15 shows a faster ignition rate which ends at 398.1 °CA at maximum brake power. This may be due to the greater accumulation and rapid burning of fuel in the uncontrolled combustion phase. The commencement of combustion is early for diesel compared to that of BDE15, BDED1\% and BDED2\%.
6.2 Engine performance analysis

6.2.1 Brake specific energy consumption

Figure 9 depicts the variation of brake specific energy consumption (BSEC) with brake power for diesel, BDE15, BDED1% and BDED2%. BSEC is a better way of indication of energy consumed in comparison with brake specific fuel consumption, when the heating value and density of two fuels are different. It is apparent from the figure that diesel shows the lowest BSEC, while BDED2% shows the highest BSEC.

Figure 9  Variation of BSEC with brake power

The higher heating value of diesel is the reason for the lower specific energy consumption compared to that of BDE15 at every brake power. The BSEC is higher for BDE15, BDED1% and BDED2% throughout the load spectrum compared to that of diesel at maximum brake power. BSEC for BDE15, BDED1% and BDED2% is found to be higher by about 2.9%, 5.6% and 8.6% respectively, at maximum brake power. In order to produce the same power output at a given brake power, the energy required is more for BDE15.

6.2.2 Exhaust gas temperature

The trend of the EGT with respect to brake power for diesel, BDE15, BDED1% and BDED2% is illustrated in Figure 10. It can be observed from the figure, that there is not much deviation in the EGT between diesel and BDE15 at maximum brake power. The value of EGT for diesel and BDE15 is 330.3°C and 326.7°C at maximum brake power. The longer ignition delay and low cetane number of BDE15 is reason for lower EGT. But for BDED1% and BDED2%, the EGT is found to be 361.8°C and 383.1°C respectively at maximum brake power, which is higher compared to diesel operation, at maximum brake power. This may be due to longer combustion duration which may extend the combustion of fuel air mixture up to the exhaust stroke and heat will available as lost in the exhaust.
Figure 10  Variation of EGT with brake power

6.3  Engine emission analysis

6.3.1  BSCO emission

Figure 11 depicts the variation of the BSCO emission with brake power. The BSCO emission is the result of incomplete combustion. As bioethanol is an oxygenated fuel, the engine operates with a still leaner mixture than that of diesel operation and hence, the BSCO formation of BDE15 and BDE15 with cetane improver is low.

Figure 11  Variation of BSCO emission with brake power

The drop in the BSCO emission for BDED1% and BDED2% is 2.38 to 0.39 g/kWh and 3.13 to 0.70 g/kWh respectively, from 25% brake power to maximum brake power. The BSCO emission for BDED2% is higher compared to that of diesel, at part load operation. This may be due to combustion deterioration, caused by the higher addition of DEE
which increases the latent heat of evaporation (Cai et al, 2004). But at maximum brake power, the BSCO emission for BDED2% is found to be lesser by about 7% than that of diesel due to complete combustion achieved by increased oxygen fraction and fuel consumption.

6.3.2 BSHC emission

The variation of BSHC emission with respect to brake power for diesel, BDED1% and BDED2% are shown in Figure 12. It is seen from the figure that the BSHC emission for BDED1% operation is the lowest compared to other fuels throughout the load spectrum. It varies from 0.2 to 0.03 g/kWh from 25% brake power to maximum brake power. The addition of DEE in small quantity promotes the ignition quality of fuels, hence lower the BSHC emission. It can also be observed from the figure that BSHC emission decreases with respect to brake power for all the tested fuel in this study. At maximum brake power, there is a considerable difference between emissions of diesel, BDE15, BDED1% and BDED2%. At maximum brake power, the BSHC emission for BDE15 and BDED1% decreases by about 14% and 21% respectively compared to that of diesel operation. The BSHC emission for BDED2% is higher compared to that of diesel, BDE15 and BDED1% throughout power output and it varies from 0.3 to 0.05 g/kWh from minimum brake power to maximum brake power.

Figure 12 Variation of BSHC emission with brake power

With higher percentage of DEE addition, the cooling effect may increase due to high latent heat of vaporisation which may also decrease the cylinder gas temperature. Flame quenching may also be the reason for higher BSHC noticed with the emulsion. This affect the amount of operating air-fuel ratio of the engine and also, a portion of the fuel-air mixture in the combustion chamber come in to direct contact with the chamber walls and quenched without burning.
6.3.3 BSNO emission

Figure 13 shows the variation of the BSNO emission with brake power for diesel and bioethanol diesel emulsion with or without cetane improver. The BSNO emission in a CI engine is a function of air-fuel ratio and combustion temperature. The BSNO emission for the BDED1% is found to be higher by about 3%, compared to that of BDE15. This is due to more cylinder temperature achieved by proper mixing of oxygen and fuel. The BSNO emission value for diesel at maximum brake power is 2.6 g/kWh. At maximum brake power, the BSNO emission for the BDED1% and BDED2% is found to be reduced by about 4% and 11.3% respectively, compared to that of diesel operation.

Figure 13 Variation of BSNO emission with brake power

[Graph showing variation of BSNO emission with brake power]

With the DEE operation, the ignition delay is shortened and the accumulation of fuel is reduced. Also with DEE, the cooling effect will increase which lowers the in cylinder temperature. The difference in the BSNO values between diesel and BDE15 with and without cetane improver is quite significant at maximum brake power, but decreases drastically from minimum brake power to maximum brake power. At minimum brake power, the latent heat of vaporisation and the viscosity of the BDE15 influence the combustion temperature predominantly and hence higher difference is noticed. As the engine brake power reaches to the maximum the cylinder temperature increases due to longer combustion duration and thus less deviation is noticed between the fuels at maximum brake power.

6.3.4 Smoke density

Figure 14 shows the variation of smoke emission with brake power for diesel, BDE15, BDED1% and BDED2%. Bioethanol has low soot tendency because of its less carbon to hydrogen ratio and also, no aromatic content. It can be observed from the figure that the smoke is the highest for diesel followed by BDE15, BDED1% and BDED2%. The reduction in smoke for the BDE15 operation is the result of better combustion, as the bioethanol is an oxygenated fuel. DEE has a higher cetane number, and added in small quantities to the BDE15, the cetane number of BDE15 may increase a little. Due to the
enhancement of combustion achieved by the addition of high cetane fuel, the smoke is found to be lower for BDE15 with cetane improvers than that of BDE15 without cetane improver throughout the load spectrum.

Figure 14  Variation of smoke density with brake power

The values of smoke for diesel and BDE15 are 25% and 24% respectively at maximum brake power. While adding the cetane improver with the BDE15, the smoke value for the BDED1% and BDED2% further decreases to 8 and 23.2% respectively at maximum brake power. DEE fuel is oxygenated and it has low carbon to hydrogen ratio. It has a positive effect on the elimination of soot formation (Cinar et al., 2010).

7 Conclusions

Experimental investigations were carried out in a single cylinder, four stroke, direct injection diesel engine fuelled with BDE15 emulsion with or without cetane improver. The proportion of bioethanol in the emulsion was 15% and the cetane improver used was DEE1% and DEE2%. The conclusions are as follows:

• The cetane delay for BDED1%, BDED2%, BDE15 varies 1 to 2 °CA compared to that of diesel.

• The BSEC is higher compared to that of diesel fuel. The BSEC for BDE15, BDED1% and BDED2% are higher by about 2.93%, 5.65% and 8.63% respectively, at maximum brake power.

• The EGT is the lowest for diesel, and the highest for BDED2%.

• The values of BSNO emission for BDE15, BDED1% and BDED2% are found to be lower by about 2.6%, 4%, and 11.3% respectively, compared to that of diesel at maximum brake power.

• The BSCO emissions drop with the addition of cetane improvers to the fuel. The drop in the BSCO emission for BDED1% and BDED2% is 32% and 7% respectively, compared to that of diesel at maximum brake power.
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- The BSHC emissions for the BDE15, BDED1% and BDED2% are found to be 0.037, 0.026 and 0.047 g/kWh respectively, at full load. The BSHC emission for BDE15 and BDED1% decreases by about 0.5 and 1.6% respectively compared to that of diesel operation at maximum brake power.

- The smoke emission reduces with the addition of diethyl ether to diesel fuel. While adding the cetane improver with the BDE15, the smoke value further decreases to 8% and 23.2% with BDED1% and BDED2% respectively, at maximum brake power.

It can be concluded that 1% of DEE on volume basis can be used as an ignition/cetane improver with the bioethanol-diesel emulsion for smooth operation and controlled emission of the engine.

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References


| Emission at full load | Parameters | $X_1$ in (g/kWh) | $X_2$ in (g/kWh) | $X_3$ in (g/kWh) | $\tau$ in (g/kWh) | $\sum_{i=1}^{n_3} (|x_i - \tau|)^2$ | $\sum_{i=1}^{n_3} (|x_i - \tau|)$ ($s$) | $s$ | $U(Y)$ in % |
|----------------------|------------|------------------|------------------|------------------|------------------|-----------------------------|-----------------|-----|-------------|
| **BSCO**             | Diesel     | 0.98238          | 0.94937          | 1.0023771       | 0.97804          | 0.001433306                 | 0.000072        | 0.02677 | 1.54546     |
|                      | BDE15      | 0.46989          | 0.47193          | 0.5186228       | 0.48681          | 0.00151974                  | 0.00076         | 0.02757 | 1.59151     |
|                      | BDED1%     | 0.38712          | 0.36101          | 0.43165         | 0.39326          | 0.00255155                  | 0.00128         | 0.03572 | 2.06218     |
|                      | BDED2%     | 0.72403          | 0.66724          | 0.7049          | 0.70206          | 0.00224258                  | 0.00112         | 0.03349 | 1.9333      |
| **BSHC**             | Diesel     | 0.040364         | 0.0555           | 0.032795        | 0.042886         | 0.00267294                  | 0.00013367      | 0.011560583 | 0.667451 |
|                      | BDE15      | 0.030136         | 0.047716         | 0.035159        | 0.03767          | 0.000163978                 | 8.19891E-05     | 0.009054784 | 0.522778 |
|                      | BDED1%     | 0.031775         | 0.018535         | 0.029127        | 0.026479074      | 9.81598E-05                 | 4.90799E-05     | 0.007006 | 0.404475    |
|                      | BDED2%     | 0.044541         | 0.057641         | 0.039301        | 0.047160814      | 0.00173481                  | 8.92403E-05     | 0.009447 | 0.545406    |
| **BSNO**             | Diesel     | 2.678            | 2.728            | 2.628           | 2.678            | 0.005                       | 0.0025          | 0.05   | 2.886751    |
|                      | BDE15      | 2.422            | 2.518            | 2.46            | 2.466667         | 0.004674667                 | 0.002337333     | 0.048345975 | 2.791256 |
|                      | BDED1%     | 2.547            | 2.609            | 2.623           | 2.593            | 0.003272                    | 0.001636        | 0.040447497 | 2.335237 |
|                      | BDED2%     | 2.355            | 2.274            | 2.301           | 2.31             | 0.003402                    | 0.001701        | 0.041243181 | 2.381176 |