Effects of using alcohols on the performance and emissions of a diesel engine

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Abstract. Addition of renewable alcohols to diesel is being investigated extensively to reduce greenhouse gas emissions. The objective of this study was to examine the suitability of such renewable alcohols. In this study, emissions and performance characteristics of alcohol/diesel blends were evaluated for a four stroke single cylinder diesel engine test rig. n-octanol and n-butanol were the alcohols considered. Experiments were conducted at different loads up to 4 kW and for alcohol contents from 10% to 40% by volume. The results indicated that the alcohol/diesel blends exhibited similar performance characteristics to that possessed by diesel. A slight drop in brake power was observed in all the blends compared to pure diesel. The brake thermal efficiency and brake specific fuel consumption increased in all alcohol blends at almost all the loads considered in the study. The emission analysis was also conducted using the AVL DI Test. The results revealed that CO and NO emissions decreased compared to pure diesel. However, HC emissions increased for n-butanol blends but they decreased in case of n-octanol blends. Results are a clear indication that these blends have an excellent potential and detailed investigations in real life conditions can lead to commercial usage.

Nomenclature:
BP : Brake power
W : Load applied with the help of a dynamometer
N : Rotational speed of the engine
Wf : Fuel consumption
x : Volume of fuel
t : Time required to consume x ml of fuel
Wdf : Specific consumption of fuel
Hf : Heat supplied by fuel
Cv : Calorific value of fuel
\\eta_{bt} : Brake thermal efficiency
\\eta_{vol} : Volumetric efficiency
ao : Cross sectional area of the orifice
Cd : Coefficient of discharge for orifice
Vs : Swept volume
H : Head causing flow of air through orifice
\\rho_f : Density of fuel

1. Introduction
Internal combustion engines are used extensively in transportation industry due to the efficiency and flexibility they offer. Greenhouse gas emissions from these engines are primarily responsible for the deterioration of air quality. 22% of carbon dioxide emissions are from transportation sector alone [1]. In the European Union, the transportation sector contributed to 19% emissions and in the United States, 27% [1]. With no reduction in the demands of these vehicles, 21st century has seen a sharp rise in the norms setup to control greenhouse gas emissions. Multiple alternatives are being explored to improve the climate scenario of the globe. One such alternative being explored is bio-fuels. Bio-fuels are being widely examined as an alternative to conventional fossil fuels due to their similarity with diesel in terms
of properties and sustainable production. Alcohols can be derived easily from biomass, hence have been investigated in several studies.

Zehra and Aksu [2] investigated the effect of using n-butanol along with diesel at very low vol/vol. ratios on the performance and emission characteristics of a diesel engine. n-butanol was considered at very low ratios (2%, 4% and 6%). Experiments were conducted at three different speeds and six different loads. Results indicated improvement in nitrogen emissions for 2% and 4% blends. Peak pressure inside the cylinder and heat release rate were not affected significantly although they were slightly higher than pure diesel for 2% concentration case at 2000 and 3000 rpm. For all three blends, smoke reduced significantly whereas HC emissions increased. These results indicated that 2% blend was ideal amongst the three possibilities. Some positive outcomes and negative outcomes led to the conclusion that alcohols were definitely promising but extensive research is still required to commercially use these bio-fuels.

Another investigation on n-butanol blends was conducted by Merola et al. [3] who investigated the combustion process via optical diagnostics. Initially, 20% n-butanol/80% diesel blend was used in a turbocharged, water cooled four-cylinder diesel engine. Later, the blend with the same composition was tested in a single cylinder optically accessible diesel engine. It was observed that controlling injection timing, pressure and oxygen concentration at intake allows benefits in terms of reduction in NOx emissions smoke. Optical investigations indicated that the butanol blend promoted faster combustion and higher concentration of OH in the combustion chamber leading to an almost smokeless condition. Although smokeless conditions were obtained, a slight increment in NOx emissions and brake specific fuel consumption were observed. Similar to n-butanol, many studies have been conducted on iso-butanol as well.

Kumar and Saravanan [4] studied the performance and emission in a single cylinder diesel engine by considering four isobutanol blends: 10%, 20%, 30% and 40% under three exhaust gas recirculation rates (EGR) 10-30% and two crank angles. Experiments revealed that NOx and CO emissions decreased with increase in iso-butanol content for all loads considered in the study. Further reductions were obtained when the crank angle was retarded by 2°. CO emissions showed an increasing trend with increasing EGR rates. Smoke opacity decreased with increasing iso-butanol content due to the availability of more oxygen. With EGR, opacity increased drastically beyond 20% iso-butanol. Hydrocarbon emissions were found to increase with increasing iso-butanol content. Only a slight reduction was obtained when the injection timing was retarded. Hence, it was concluded that the blends could successfully reduce emissions but with a slight drop in performance. Performance of iso-butanol/diesel blends was also studied recently by Karabektas and Hosoz [5]. The volume concentration of iso-butanol varied from 5-20%. Basic performance parameters namely brake power, brake thermal efficiency and brake specific fuel consumption were calculated along with an emission analysis. Blends were tested in a four stroke diesel engine at different speeds and at the full load conditions. There was a reduction in brake power for all the test cases due to low energy content of iso-butanol. The decrease in brake power is substantial for iso-butanol concentration greater which is greater than 10%. Also, there was an increment in brake specific fuel consumption for all the blends considered directly proportional to iso-butanol content. Results also indicated that the blend containing 10% iso-butanol yielded the highest brake thermal efficiency at high speeds. Use of these blends led to a decrement in NOx and CO emissions but HC emissions increased.

X. Gu et al. [6] recently compared the performance of two alcohol blends in a diesel engine. N-butanol and iso-butanol were separately mixed with diesel in different proportions at the rate of, 15% and 30% for both alcohols. Experiments were conducted at a fixed low engine speed of 1000 rev/min, light and medium loads equal to 0.3 and 0.5 MPa and different ignition timings as far as 6° and different EGR rates. Results indicated that an iso-butanol diesel blend had a longer ignition delay, longer duration of premixed combustion, higher peak pressure and higher HRR than the n-butanol blend. Both blends reduced soot emissions with a very little variation in NOx emissions. NOx and soot emissions were simultaneously reduced by retarding the ignition timing and lowering EGR rates with very little effect on the performance of the engine. Another comparative study was conducted between 1-butanol/diesel and 1-pentanol/diesel blends by J. Campos-fernández et al. [7]. The butanol concentration was varied.
from 10-30% whereas the pentanol concentration was varied from 10-25%. All tests were conducted on a three-cylinder water cooled direct injection diesel engine. Experiments indicated that combustion in both the blends was better compared to pure diesel. The presence of oxygen in the blends is possibly responsible for better combustion despite the blends having a lower heat value. The brake thermal efficiency also increased for the blends but torque and power were similar to that obtained in case of diesel. The brake specific fuel consumption was better for butanol blends than for the pentanol blends and pure diesel. It was also deduced that since butanol and pentanol have properties similar to that of diesel, better behaviour can be obtained from higher blends instead of lower blends. Although, butanol and pentanol may not entirely replace diesel, a higher percentage of these blends can be used instead of using 100% diesel. Choudhary et al. [8] investigated the use of acetylene in conjunction with diesel in multi fuel engine. Jamrozik et al. [9] and Yusri et al. [10] analysed the performance and emissions of compression using of alcohol fuels. Bae and Kim [11] presented a comprehensive review for potential alternative fuels for automotive engine. Tutak et al. [12] investigated the influence of methanol and E85. Prakash et al. [13] investigated the optimum ternary fuel blend with neat castor diesel bio-ethanol for a diesel engine.

A recent study on another long chain alcohol was carried out by Kumar et al. [14]. They examined the emission and performance characteristics of a diesel engine with n-octanol/diesel blends up to 30% n-octanol under EGR and naturally aspirated modes. n-Octanol can be synthesized using microbes E-coli and clostridium. Due to this ease of production, analysis of n-octanol in diesel engines has become relevant. Experimental data indicated an ignition delay for all blends due to lower cetane number. This ignition delay resulted in higher peak pressures and high HRR and thus a better combustion phase was obtained. Brake thermal efficiency increased and brake specific fuel consumption decreased with increasing concentration of n-octanol for the naturally aspirated mode. Both these performance parameters suffered with EGR mode. Emission analysis indicated a decrease in NO\textsubscript{x} concentration with increasing content of n-octanol. Higher NO\textsubscript{x} reductions were obtained at increased EGR rates. Smoke opacity also decreased with increasing n-octanol content for the naturally aspirated case but it increased with increasing EGR rates. HC and CO emissions were low for all the naturally aspirated cases but were negatively affected with the introduction of EGR, although they were still lower than the emissions obtained in case of pure diesel.

Zhang et al. [15] considered four different types of alcohol/diesel blends and examined them in light duty and a heavy duty engine. n-butanol and n-octanol were the alcohols considered in this study. Hydro-treated vegetable oils and di-tertiary butyl oxide were separately added to the blends. The oils were responsible for increasing the cetane number of the blend. Addition of alcohols reduced the cetane number and hence these oils helped in maintaining cetane number. In the low duty engines, the heat release profiles for the blends and diesel are almost coincident. Combustion was a bit faster and PM decreased with increasing content of the blends. Faster combustion led to a higher indicated thermal efficiency than diesel. The soot emissions also reduced which indicates that the alcohols considered performed effectively.

The present investigation analyses the performance parameters and emissions for a single cylinder diesel engine test rig using three alcohols: n-butanol and n-octanol, similar to those considered by Zhang et al. [15]. The longer carbon chain molecules were more suitable for conducting tests as they have high cetane number, high flash point, high density and higher heating values closer to that of diesel when compared with short carbon chain molecules like methanol and ethanol. Various performance parameters namely brake power, brake thermal efficiency, volumetric efficiency and brake specific fuel consumption were calculated for each alcohol/diesel blend at different concentrations of the alcohol. Emissions were also analysed for each test case using AVL DI Test.

2. Experimental setup
Experiments were conducted on a conventional single cylinder 4 stroke water cooled diesel engine test rig loaded by an electric brake dynamometer. Technical specifications of the engine are provided in table 1. Figure 1 shows the schematic data of single cylinder experimental test rig. The test rig
Arrangement consists of a fuel tank mounted on a stand with a burette facilitating measurement of the amount of fuel used for the test. The volume of air sucked is calculated using a manometer and an orifice meter.

The test rig also allows for the measurement of flow rate and temperature of cooling water with the help of a water meter and temperature sensors respectively. The figure above clearly indicates the location of thermocouples. These measurements are indicative of the amount of heat carried away by the cooling water. Similarly, the heat carried away by the exhaust gases is measured by an exhaust gas calorimeter. It consists of a central tube through which exhaust gases pass and an outer jacket through which water is passed. The measured temperature of exhaust gases coupled with the measurement of flow rate of water through the jacket indicates the amount of heat carried away by the gases. The emission measurements were performed using AVL DI Smoke 480. The specifications of DI Smoke analyser are provided in Table 2. Figure 2 shows the experimental setup and the AVL DI Test equipment.

Table 1: Engine Specifications.

| Engine type   | Diesel Engine |
|---------------|---------------|
| No of cylinders | 1             |
| Bore x Stroke  | 80 x 110 (mm x mm) |
| Compression ratio | 16.5:1       |
| Cubic Capacity  | 0.553         |
| Rated speed    | 1500 rpm      |
| Rated output   | 3.7 kW        |
| Fuel capacity  | 6.5 L         |

Figure 1: Schematic presentation of the single cylinder engine.

Table 2: Specifications of AVL DI Smoke analyser.

| Measuring principle | Extinction measurement | Adhering to measurement accuracy |
|---------------------|------------------------|----------------------------------|
| Operating technique | +5…….+45              |                                  |
|                     | +1…….+50              |                                  |
| Turbidity           | Measuring Range        | Resolution                       |
|                     | 0-100%                 | 0.1%                             |
| Absorption (k value)| 0-99.99 1/m            | 0.01 1/m                         |
3. Materials and methodology
In the present investigation, experiments were conducted at different loads 0-4 KW in increments of 1KW. The load was varied with the help of an electric brake dynamometer. Commercially available diesel fuel was used for all experiments and alcohols were purchased from a local distributor. Blends were prepared just before conducting the experiments. Visual observations indicated that the blends were homogeneous and faced no stability issues. n-Octanol and n-butanol were the alcohols considered in the analysis. Investigations on longer chain carbon molecules have indicated that the heating values, density and flash point of longer chain molecules are closer to that of diesel. Solubility of longer chain alcohols is higher in diesel compared to the solubility of methanol and ethanol. Hence, the given alcohols were used in the experiments. The properties of the alcohols have been listed in table 3 [15]. Different amounts of alcohol were mixed with diesel. The concentration range for all alcohols was the same. It was varied from 10% to 40% by volume basis in increments of 10%. The blends were assigned a specific name depending on alcohol and diesel content as follows: D100 was 100% diesel, D90B10 was 90% diesel and 10% butanol, similarly the name D(X)O(Y) for n-octanol where X and Y are percentages of diesel and alcohol respectively.

Fuels were not pre-heated. The operating temperature and pressure of fuel in each test case were equal to the ambient conditions. Before conducting each experiment, the diesel engine was run for almost 30 minutes so that the leftover fuel from the previous tests present in the connecting tubes was consumed. Once the leftover fuel was consumed, tests were conducted. Each experiment was conducted so as to allow the combustion to reach a steady state. Between two experiments, there was a substantial gap in terms of time in order to cool down the engine, because failure in ensuring reasonable gap would give way to incorrect results.

4. Engine performance parameters
The performance of an internal combustion engine is gauged with the help of multiple parameters namely brake power, brake thermal efficiency, volumetric efficiency, mechanical efficiency, mean
effective pressure, brake specific fuel consumption etc. Brake power corresponds to the power output at the drive shaft of the engine. The brake thermal efficiency is a ratio of brake power to the input energy of the fuel. Volumetric efficiency is a measure of deviation between the amount of air-fuel mixture that actually enters the cylinder and the amount of air-fuel mixture which would enter in ideal conditions.

This section presents the standard correlations which are used to calculate these engine performance parameters. The brake power, brake thermal efficiency, volumetric efficiency and brake specific fuel consumption have been evaluated for each test case using formulae given in [16].

\[
BP = \frac{WXN X0.746}{2000} kW
\]  
(1)

\[
W_f = \frac{x X \rho_f}{t X10^6} kg/sec
\]  
(2)

\[
W_s f = \frac{W_f}{BP} kg/kW - sec
\]  
(3)

\[
H_f = W_f X C_o kW
\]  
(4)

\[
\eta_{bt} = \frac{BP X 10^6}{H_f}
\]  
(5)

The emission data was captured electronically for each test case using a computerised AVL test.

\[
\eta_{vol} = \frac{Q_a X 100}{V_s}
\]  
(6)

\[
Q_a = C_d X a_0 X (2 X g X H)^{0.5}
\]  
(7)

5. Results and discussions

This section presents experimental results in the form of comparative figures relating to the effects of using alcohol/diesel blends on the engine performance and emission characteristics.

5.1. Performance analysis

5.1.1. Brake power

Brake power is an indication of the amount of work done by the fuel in unit time [17]. The variation of brake power with respect to the applied load for different alcohol blends considered in this study. The brake power of blends has been compared with the results obtained with pure diesel in same test conditions.
Figure 3. Variation of brake power for the alcohols/diesel blends for n-Butanol and n-Octanol diesel blends.

The brake power for all blends considered is comparable in magnitude to that of pure diesel as shown in Fig 3. It was found that, with increasing load, the brake power increased significantly for all the blends. Two factors primarily govern the brake power variation for the blends. First is the heating value of alcohol whereas the second factor is concerned with the availability of oxygen. As shown in the figure, the first factor plays a vital role in blends with lower alcohol contents leading to lower brake power as compared to diesel, whereas for blends with higher percentages of alcohol, the availability of sufficient oxygen paves the way for a rather complete combustion, leading to increased power despite the lower heating value of alcohols. Although, the brake power is lower than diesel even for the higher alcohol blends, the value is more than that for lower alcohol blends.

The trend obtained in figure 3, is entirely uniform in nature with some deviations from the ideally expected solution. Deviations are possibly due to a minor non-homogeneity in the blends resulting in sudden changes in some parameters in some cases. Deviations can be avoided by preparing blends using sophisticated techniques to avoid any non-homogeneity.

Figure 4. Variation of brake specific fuel consumption for n-Butanol and n-Octanol diesel blends.

5.1.2. Brake specific fuel consumption and specific energy consumption

Brake specific fuel consumption defined as the ratio of fuel consumption to the brake power generated is another parameter relevant to the performance of a diesel engine. It is a measure of how effectively the fuel is combusted. Figure 4 indicates that the brake specific fuel consumption decreases with increasing load for all blends considered in the study because the heating value of the blends is the low than that of diesel. A lower heat content of blends leads to more consumption of fuel to produce the same effective power. Previous studies [18] have obtained a similar trend for other alcohol/diesel blend.
validating reliability of the results. The figure also indicates that the minimum value of fuel consumption is obtained in case of pure diesel at each of the applied loads. When the specific consumption of blends is compared with each other, no particular trend is obtained. Many possibilities exist due to which there is an absence of trend. As discussed previously, two factors namely heating value and oxygen content govern combustion characteristics of a fuel. It is possible that these two factors may not respond linearly to the applied loads and therefore no uniform trend was obtained for the given test cases. The non-linearity may also be due to the non-homogeneity of some samples. Hence, specific fuel consumption and specific energy consumption with respect to load for the blends is calculated and presented. Figure 4 shows the variation of brake specific fuel consumption for n-butanol/diesel and n-octanol/diesel blends, whereas variation of brake specific energy consumption for n-butanol/diesel and n-octanol/diesel blends is given in figure 5.

5.1.3. Brake Thermal Efficiency
The relation between input and output is an appropriate parameter to gauge the performance of any given system. Brake thermal efficiency (BTE) is one such relation equal to brake power generated at the shaft divided by heat content of the fuel. The variation of brake thermal efficiency for the test cases considered in this analysis has been presented in Figure 6. The figure 6 indicates that brake thermal efficiency increases with load for all the blends considered in this study. It was noted that the BTE obtained in case of pure diesel was more than any n-butanol/alcohol blend at any given load. The brake thermal efficiency was lower for low n-butanol/diesel blends. However, it increased with further addition of alcohol possibly due to improved combustion characteristics attained via presence of excess oxygen. For the n-octanol/diesel blends, the BTE efficiency was not affected much by the addition of n-octanol with almost no variation at lower and medium loads due to relatively closer heating values of diesel and n-octanol.

![BTE vs Load for n-butanol blends](image1)

![BTE vs Load for n-octanol blends](image2)

**Figure 6.** Variation of brake thermal efficiency for for n-Butanol and n-Octanol diesel blends.

5.2. Emission Analysis
The analysis of any engine is incomplete without considering emissions. The performance analysis indicated that the blends have properties comparable to that of diesel but their commercial utility is totally dependent on the combination of performance parameters and emissions. This section discusses the emissions of the blends considered in this study.

5.2.1. NO\(_x\) emissions
Nitrogen oxides are a family of polluting chemical compounds [14] which affect the air quality significantly. Different mechanisms have been proposed to explain the formation of different NO\(_x\) compounds [19]. The NO\(_x\) emissions are mainly dependent on the combustion temperature and the availability of excess oxygen. The variation obtained in this study is shown in Figure 7. It can be seen
in the figure 7 that NO emissions initially increased with increasing load up to a certain load but decreased as the load was further increased. The trend obtained was similar for all both alcohols considered in this study. Another observation is that NO emissions are lower than that of diesel at all loads for most of the blends which can be attributed to lean composition of the fuel and the temperature lowering effect of the blends [18]. The energy content of the blends is lower compared to pure diesel due to low heating values of the alcohols. Lower energy content coupled with higher latent heat of evaporation of the blends results in an overall drop in temperature. Certain deviations were obtained possibly due to a slight non-homogeneity of the blends or due to minor experimental errors.

5.2.2. CO emissions
The CO emissions are extremely vital to the engine analysis as they qualitatively represent the smoke emitted by the diesel engine. The variation of CO for the different alcohol/diesel blends has been provided in the figure 8. The CO emissions were low at all the applied loads for all the blends considered. CO emissions decreased with increasing load up to medium loads due to increasing temperature but increments were obtained for most blends at higher loads. The leaning effect of alcohol ensured that the CO emissions were lower compared to the emissions obtained in case of pure diesel at all the applied loads. The results were also indicative of the fact that maximum reduction in CO compared to diesel is obtained at the highest possible load considered in this study.

5.2.3. HC emissions
The HC emission variation has been depicted in the figure 9. The variation of HC emission for n-octanol/diesel blends was different from the n-butanol/diesel blends. HC emissions decreased with increasing n-octanol content which is in agreement with the results obtained by Kumar et al. [14]. This is possibly due to increasing oxygen content which led to oxidation of unburnt HC. The results also indicated that the HC emission was less than that of pure diesel for all the blends of n-octanol. The behaviour was different for the n-butanol blends possibly due to poor combustion characteristics of the blends. The blends possess a higher latent heat of vaporization which slows down evaporation [20]. This slow down coupled with poor air-fuel mixing leads to incomplete combustion. The results suggested that for almost all blends of n-butanol, the HC emissions were more than that of pure diesel.

![Figure 7. Variation of NO emissions w.r.t load for n-Butanol and n-Octanol diesel blends.](image-url)
Figure 8. CO emission variation w.r.t load for n-Butanol and n-Octanol diesel blends.

Figure 9. HC emission variation w.r.t load for n-Butanol and n-Octanol diesel blends.

6. Conclusion
The performance and emission characteristics of different alcohol/diesel blends were evaluated on a four stroke single cylinder diesel engine at different loads and compared with pure diesel values. Based on the results, the following conclusions can be drawn:

- n-butanol and n-octanol are easily miscible in diesel as homogeneous blends were obtained with no separation issues.
- Brake power was lower compared to diesel for all the blends at almost all loads considered possibly due to lower heating value of alcohol. Brake power increased with increasing loads for the blends considered in this study.
- The experiments yielded a higher bsfc for all the blends compared to diesel due to inverse relation of bsfc with the energy content of fuel.
- The brake thermal efficiency increased with load for all the blends considered in this analysis. The addition of n-octanol did not affect BTE. However, BTE of n-butanol blends was affected by the amount of alcohol present. This was possibly due to the influence of higher oxygen at higher alcohol contents which improved combustion characteristics leading to a better thermal performance.
- Emission analysis revealed that CO, NO and HC emissions were low compared to pure diesel for all n-octanol/diesel blends. However, the trend was different for the n-butanol/diesel blends. In summary, the alcohols considered in this study are excellent alternative to pure diesel and have huge potential for use in commercial engines with performance characteristics similar to that of diesel and lower emissions.
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