Performance and emissions characteristics of a variable compression ratio engine operated on dual fuel mode using diesel and biodiesel with additives

K Sundar¹,², R Udayakumar²

¹ Research Scholar, Department of Mechanical Engineering, BITS Pilani – Dubai Campus, UAE
² Professor, Department of Mechanical Engineering, BITS Pilani – Dubai Campus, UAE
³ Corresponding Author E-mail: sundarmpk@gmail.com

Abstract. The world today is mainly dependent upon non-renewable fuel sources for power generation. This research work focuses on the impact of additives for biodiesel to reduce the emissions and retrieve the performance. The fuel additives play a vital role in decreasing the limitation of biodiesel, would be considered to decrease the emissions, improve combustion and fuel economy. Experiment are operated on single-cylinder, four-stroke, variable compression ratio and compression ignition engine. Tests are conducted with diesel, biodiesel, diethyl ether mixed with biodiesel and toluene mixed with biodiesel, and also at various percentages (1%, 2.5% and 5.0%) of additives by volume. The performance and emissions data's are obtained from experimentation were studied and a detailed analysis was carried out for each of the blends by comparing with diesel and biodiesel blend B20. The diethyl ether and toluene additives blends showed a simultaneous decrease in CO, CO₂, HC and NOx. These additives were improved at higher engine brake power, lower specific fuel consumption and higher brake thermal efficiency than biodiesel blend B20. The result reveals that the 5% of DEE-biodiesel blend and 5% of toluene-biodiesel blend is the most effective combination with biodiesel.

Keywords: Compression ratio, Compression ignition; Methyl ester cotton seed oil; Methyl ester rice bran oil; Variable compression ratio; Diethyl ether; B20 (20%Biodiesel & 80% Diesel)

1. Introduction

The increase in population and change in life style results in increasing the consumption of energy. The energy consumes mainly in transportation and power generation. Outcome of polluted environment due to non-renewable resources have motivated scientist to research renewable sources that can reinstate fossil fuels. Amidst of all renewable resources, biodiesels have acknowledged as they are harmless and renewable. Utilization of biofuels enhances the life of the diesel engine and directly utilized without further change. The future of the transportation sector mainly depends on the contribution of biodiesel. By 2020 all new governance of European Union members have state that minimum usage of 10% of renewable energy as fuel should be used in all forms of transport [1]. Southeast Asia’s such as China and India energy require about 75% by 2030 [2]. The requirement of fossil fuel is increasing constantly. This is the major reason researchers and scientists are considering biodiesel as major source. Utilizing the biofuels in diesel motors could diminish the carbon monoxide, unburnt hydrocarbons emissions as well as increasing the NOx.

At present scenario various additives are used to enhance the characteristics of biodiesel results in increasing the performance level and also it helps to maintain the emission standards. The choice of the additives mainly depends upon the limitation of biodiesel properties. The combination of additives is not standardized. The oxygenated additives act as an important agent in diesel motor. It is very effective in enhancing the combustion process. The oxygenated additive burns the fuel without transmitting any huge extent of impotent material. Alcohols, ether and ester are major oxygenated additives [3]. The smoke emission and ignition temperature will be reduced by the adding oxygenated additives in the diesel engine. The biodiesel efficiency would be increased by oxygenated additives.
which results in decreasing the environment pollution.

The excellent characteristics of DEE as appeal a worldwide attention for reducing emissions with their presence of high cetane number and great volatility. DEE has parameters such as high cetane number, high volatile, feasible energy density and 21% by weight oxygen content as correlated with diesel. The flame speed of vegetable oil is improved as the presence of glowing acceleration in DEE is very huge. Shorter ignition delay, reduced combustion is expected with DEE injection related to vegetable oil as the presence of high cetane number in DEE [4]. Toluene is aromatic hydrocarbon which is clear water insoluble liquid with smell of paint thinners. It is also called as Methylbenzene with chemical formula C₆H₅CH₃ [5, 6].

Mohanan et al., [7] A test was operated on a four stroke diesel engine along various combination of DEE and diesel. Test outcome were found a certain 5% DEE blend increase the brake thermal efficiency of diesel engine. CO emission, smoke levels were reduced for 5% DEE blends. 5% DEE-Diesel is the suitable blend. Iranmanesh et al., [8] using blends of DEE-diesel concluded that the thermal efficiency was increased by 6.29% with 5% DEE blends due to enhancement in premixed combustion and improvement in diffusion combustion. The NOx emissions reduced with DEE usage. Also the higher oxygen content of blends results to lower hydrocarbon and smoke emissions compared to base fuels. Kapilan et al., [9] stated that higher brake thermal efficiency results from DEE-diesel blends. CO and HC emissions are decreased and NOx emissions were seen to increase with the blends. Pugazhvadivu et al., [10] concluded, 20% of DEE presence will be favorable in decreasing NOx emissions correlated to 10% DEE will be utilized in the mixture of Diesel, Pongamia biodiesel and DEE.

D.H.Qi et al., [11] Test was conducted to examine the outcome of DEE and ethanol mixture among diesel. It is found that smoke emissions are decreased. C. Swaminathan et al., [12] Concluded that fish oil biodiesel blend with 2% DEE decreased emission and recommended as the optimum preference for operating the engine with Exhaust Gas Recirculation. Fattah et al., [13] Experimental analysis of a compression ignition engine fuelled with 20% of Calophyllum inophyllum biodiesel mixture with different oxidation inhibitors. The addition of antioxidant additives enhances the engine power output. The results imply that 20% of Calophyllum inophyllum biodiesel showed the increased NOx and decreased CO and HC emission. Devaraj et al., [14] examined the effectiveness of diesel engine fuelled by mixture of waste plastic pyrolysis oil and DEE in ratio of 5% to 10% of DEE. The experiment results showed that brake power and brake thermal efficiency higher with blends of waste plastic pyrolysis oil. about which, 10% blend achieved the maximum brake thermal efficiency. At greater engine speeds, brake specific fuel consumption for waste plastic pyrolysis oil mixtures are nearer to baseline fuel. The inclusion of DEE to waste plastic pyrolysis oil CO and HC emissions reduced.

Ramavanth Konda Naik et al., [6] Experiment were conducted on single cylinder, four stroke diesel engine. Experiment was conducted with Pure Diesel, Acetone mixed with Diesel, Xylene mixed with Diesel and Toluene mixed with Diesel. Experiments were conducted at various percentages (0.5%, 0.7%, 0.83% and 1.0% etc.) of additives by volume. It is evident that the brake thermal efficiency is increased and specific fuel consumption is decreased at 1% Toluene correlated to fuels with various additives. M.Vijay Kumar et al., [2] conducted the test on diesel engine. Brake Specific Fuel Consumption and emissions are reduced due to the presence of oxygenated additives. Butylated hydroxyl toluene slightly increases the brake thermal efficiency. Antioxidant plays a vital role in controlling the NOx emission.

Across the world scientist and researchers used various additives utilized in biodiesel combination to enhance the performance and reduce the pollutants. Based on an extensive review of article oxygenated additives and antioxidant additives are selected as source for the current research work. The additives selected to conduct the research work are oxygenated additives and antioxidant additives are DEE and toluene respectively [1-16]. This research work biodiesel chosen to conduct the experimentation is cotton seed oil and rice bran oil.

2. Experimental Methodology
2.1 Experimental Setup
The engine experiments were operated on single cylinder, four strokes at stable speed diesel engine. The VCR engine specifications are presented in Table 1. An experimental system is evolved to evaluate the performance and emission aspect of a VCR engine sustain with dual biodiesel, DEE and its mixture with diesel and biodiesel, toluene and its combination with diesel and biodiesel. Table 2 represents the
measuring devices and testing methods for measuring the fuel properties. Hydrometer is used to measure the density and redwood viscometer is used to measure the viscosity of the biodiesel. The viscosity value is the number of seconds that require for 50ml of oil to flow out of a standard viscometer at a definite temperature. An important property of the bio-diesel that determines the suitability of the material as alternative to diesel fuels is the calorific value. It is measured in a bomb calorimeter according to the ASTMD240 standard method. With an oxygen container an oxygen bomb was pressurized to 3MPa. The bomb was fired automatically. Ignition quality tester is used to measure the cetane number of the biodiesel. It is defined as the percentage by volume of normal cetane in a combination of normal cetane and α-methyl naphthalene. Flash points of the biodiesel are waved using an automated Pensky-Martens closed cup apparatus. Table 3 shows the specifications of biodiesel, DEE mixture with diesel and Table 4 represents the specifications of biodiesel, toluene mixture with diesel. Table 5 represents the specifications of DEE and Table 6 presents the specification of toluene.

The test rig enables to analysis the variable compression ratio engine performance. The VCR diesel engine exhaust is connected with AVL Diagas Analyzer. The exhaust gas tester weights the exhaust pollutants. The engine was started at without load. It was permitted to process (for around 20 to 30 minutes) till the constant state condition was attained. Fuel calculating device and stop watch is used to measure the fuel consumption. The time duration for the consumption of 0cc to 20cc of fuel was evaluated. Power output, rpm, exhaust temperature and emissions were measured. The engine was loaded step by step with in the allowable limit. Performance standard were then implemented on the engine with diesel to provoke the base line data and finally biodiesel blend B20, biodiesel-DEE blend and biodiesel-toluene blend was used. The test data’s of biodiesel-DEE and biodiesel-toluene mixture were measured and correlated with diesel and biodiesel blend B20.

Table 1  Technical specification on experimental setup

| Description       | Engine Specification                                                                 |
|-------------------|---------------------------------------------------------------------------------------|
| Make & Model      | Kirloskar Oil Engine, TV1                                                              |
| Engine            | Type - single cylinder, four-stroke Diesel, water cooled, rated power 3.5 kW at 1500 rpm, stroke 110 mm, bore 87.5 mm, 661 cc to VCR engine CR range 15 to 18 |
| Dynamometer       | Type eddy current                                                                      |
| Peak cylinder pressure | 77.5 kg/cm²                      |
| Maximum speed     | 2000 rpm                                                                              |
| Minimal idle speed| 750 rpm                                                                               |
| Minimal operating speed | 1200 rpm                              |
| Fuel injection limit | 23° BTDC                  |
| Dimensions        | W 2.0 X D 2.5 X H 1.5 m                                                               |

Table 2  Measuring devices and test methods for measuring fuel properties.

| Properties          | Test Standard | Measuring Instruments |
|---------------------|---------------|-----------------------|
| Density             | ASTM D941     | Hydrometer             |
| Viscosity           | ASTM D445     | Red wood viscometer   |
| Calorific value     | ASTM D240     | Bomb calorimeter       |
| Cetane number       | ASTM D613     | Ignition quality tester|
| Flash and fire point| ASTM D93      | Pensky martens apparatus|
Table 3 Fuel Properties of diesel, biodiesel (B20) and biodiesel blends with DEE additive

| Properties                  | Diesel | B20 | B19 + 1% DEE | B17.5 +2.5% DEE | B15 + 5% DEE |
|-----------------------------|--------|-----|--------------|-----------------|-------------|
| Density (kg/m³) @ 15º C     | 815    | 828.5 | 826.8        | 824.2           | 820.0       |
| Viscosity (mm²/s) @ 40ºC    | 2.57   | 3.2  | 3.12         | 3.04            | 2.91        |
| Calorific Value (MJ/Kg)     | 45.20  | 44.15 | 44.12        | 44.08           | 44.00       |
| Cetane Number               | 51     | 51.8 | 52.31        | 53.38           | 55.15       |
| Flash Point (º C)           | 53     | 75.4 | 73.35        | 70.28           | 65.15       |

Table 4 Fuel properties of diesel, biodiesel blends (B20) and biodiesel blends with toluene additive

| Properties                  | Diesel | B20 | B19 + 1% Toluene | B17.5 +2.5% Toluene | B15 + 5% Toluene |
|-----------------------------|--------|-----|------------------|---------------------|-----------------|
| Density (kg/m³) @ 15º C     | 815    | 828.5 | 828.3           | 828.0              | 827.6         |
| Viscosity (mm²/s) @ 40ºC    | 2.57   | 3.2  | 3.13            | 3.05               | 2.93          |
| Calorific Value (MJ/Kg)     | 45.20  | 44.15 | 44.16           | 44.17              | 44.19         |
| Cetane Number               | 51     | 51.8 | 51.24           | 50.71              | 49.82         |
| Flash Point (º C)           | 53     | 75.4 | 73.79           | 71.38              | 67.35         |

Table 5 Fuel Properties of DEE additive [17-19]

| Properties                  | DEE   |
|-----------------------------|-------|
| Density (kg/m³) @ 15º C     | 714   |
| Viscosity (mm²/s) @ 40ºC    | 0.23  |
| Calorific Value (MJ/Kg)     | 36.84 |
| Cetane Number               | 125   |
| Flash Point (º C)           | -40   |

Table 6 Fuel Properties of Toluene additive [20]

| Properties                  | Toluene |
|-----------------------------|---------|
| Density (kg/m³) @ 15Deg C   | 865     |
| Viscosity (mm²/s) @ 40Deg C | 0.59    |
| Calorific Value (MJ/Kg)     | 40.59   |
| Cetane Number               | 18.3    |
| Flash Point (Deg C)         | 4       |
3. Result and Discussion
The experiments conducted for performance and emission analysis, interpreted with the results obtained. Prior to the sequence of tests, the engines that are prepared for the experiment is evaluated by performing the engine by baseline diesel fuel. The experiments are examined at various loads from 0kg to 12kg, at different preset compression ratios CR15, 16, 17 and 18. Table 7 shows the Nomenclature of fuel. The different emission characteristic curves obtained based on the experimental results are followed. 0kg has not been considered for a clear interpretation of various curves. Following are the different emission characteristic curves obtained based on the experimental results. 0kg is not considered for clear interpretation of various curves.

| Name of the fuel     | Fuel composition                        |
|----------------------|-----------------------------------------|
| Diesel               | Diesel 100%                             |
| B20                  | Diesel 80%, MECSO & MERBO 20%           |
| B19+1%DEE            | Diesel 80%, MECSO & MERBO 19%, DEE 1%   |
| B17.5+2.5%DEE        | Diesel 80%, MECSO & MERBO 17.5%, DEE 2.5% |
| B15+5%DEE            | Diesel 80%, MECSO & MERBO 15%, DEE 5%   |
| B19+1%Toluene        | Diesel 80%, MECSO & MERBO 19%, Toluene 1% |
| B17.5+2.5%Toluene    | Diesel 80%, MECSO & MERBO 17.5%, Toluene 2.5% |
| B15+5%Toluene        | Diesel 80%, MECSO & MERBO 15%, Toluene 5%   |

3.1 Brake Power
The deviations in brake power at different load for various blends are shown in Fig.1. When the load is high it results in high torque and brake power. Brake power of biodiesel-DEE blend is lower by 12.8% and biodiesel-toluene blend is lower by 11.5% compared to diesel. Brake thermal efficiency 4.7% was higher with adding DEE and 5.8% was above by adding toluene compared to B20. Biodiesel-DEE blend produced higher brake power due to their lower viscosity, which influences combustion. The higher calorific value in the toluene supports the complete combustion of the fuel for increasing the brake power. DEE has higher oxygen content and good atomization contributes a higher combustion efficiency, which resulted in higher brake power [1].

![Figure 1: Variation of BP with Load for Different Blends at CR18](image-url)
3.2 Brake Thermal Efficiency

The differences in Brake thermal efficiency at different load for various blends are represented in Fig.2. When the load increases, the Brake thermal efficiency also raised for all the combination of fuel. Brake thermal efficiency of biodiesel-DEE blend is lower by 1.6% and biodiesel-toluene blend is lower by 1.0% compared to diesel. Brake thermal efficiency 2.6% was higher with adding DEE and 3.2% was increased with adding toluene compared to B20. The DEE was achieved for earlier ignition which concluded in complete burning of fuel. The existence of oxygen in the DEE enhances the entire combustion of the fuel increasing the brake thermal efficiency. The toluene blend results in higher BTHE due to more calorific value. The DEE blend enhances an initial start of heat release during premixed combustion phase that favors the increase in brake thermal efficiency [21].

![Figure 2](image)

**Figure 2** Variation of BTHE with Load for Different Blends at CR18

3.3 Brake Specific Fuel Consumption

The variations in Brake specific fuel consumption at different load for different combination are represented in Fig.3. Biodiesel blend percentage increases, the BSFC increases. The BSFC is maximum for lesser loads and it reduces rapidly with increases in weight. BSFC of biodiesel-DEE blend is increasing by 13.9% and biodiesel-toluene blend is increasing by 12.7% compared to diesel. BSFC 3.9% was decreased with adding DEE and 5.4% was decreased with adding toluene compared to B20. The minimum BSFC of biodiesel-DEE combination may be as a result to the existence of more oxygen in DEE molecule, which results to complete burning of fuel. BSFC decrease due to higher output of biodiesel-toluene blend. As the result, a high volatile characteristic of DEE leads to speed the blending of air-fuel mixture and hence, speeds up the combustion process [11]. DEE has a lesser calorific value and higher latent heat of vaporization compared to diesel fuel, which can lead to a decrease in engine efficiency and an increase in fuel consumption [21].
3.4 Carbon Monoxide

The differences in carbon monoxide at various loads for different blends are represented in Fig.4. CO emission is tasteless, colorless and odorless toxic gas. CO emission of biodiesel-DEE blend is decreased by 36.2% and biodiesel-toluene blend is decreased by 34.5% compared to diesel. CO emission 6.4% was decreased with adding DEE and 5.0% was decreased with adding toluene compared to B20. The higher cetane number results better combustion and shorter ignition delay. The shorter ignition delay period of biodiesel-DEE blend promote the combustion and decrease the CO emission. The CO emissions level dependent on the air/fuel ratio. The lowest emissions are consistent with excess air. Biodiesel-toluene blend have low viscosity which results in the lower possibility of formation of rich fuel zone and thus decrease CO emissions. The molecular oxygen in DEE also improves the combustion leads to better oxidation of the fuel air mixture. The increase in cetane number of DEE acts as an ignition improver reduces the combustion duration indicating improved rate of combustion, resulting in a lower CO emission [22].

3.5 Carbon Dioxide

The variations in carbon dioxide at various loads for distinct blends are represented in Fig.5. At low loads, CO₂ emissions are low as the equilibrium reaction between CO and CO₂ shifts in favor of CO formation. With increase in load, air fuel ratio becomes richer and thus increased fuel is burnt forming more CO₂ emissions. The oxygen quantity contains in biodiesel causes the higher carbon dioxide. The CO₂ emissions with biodiesel-DEE blends and biodiesel-toluene blend are higher than those with diesel fuels due to better combustion with fuel-borne oxygen. CO₂ exhalation of biodiesel-DEE blend is increased by 14.9% and biodiesel-toluene blend is increased by 14.6% compared to diesel. CO₂ emission 1.0% was increased with adding DEE and 0.7% was increased with adding toluene compared to B20.
3.6 Unburned Hydrocarbon

The differences in unburned hydrocarbon at various loads for distinct blends are presented in Fig.6. HC emission of biodiesel-DEE blend is decreased by 7.0% and biodiesel-toluene blend is decreased by 6.3% compared to diesel. HC emission 2.8% was lowered by adding DEE and 2.1% was lowered by adding toluene compared to B20. Incomplete burning fuel inside the cylinder promotes the creation of HC. Biodiesel-DEE blends initiate an early begin of combustion due to low boiling point. Hydrocarbons emissions are the records for the left out unburnt hydrocarbons in the exhaust gases owing to the lack of oxygen and improper combustion. The increased load resulted in higher HC emissions for all tested conditions. This enhances the oxidization of the hydrocarbon fuels, resulting to better combustion with a reduction in HC emission [23]. HC emissions are reduced for biodiesel-DEE blend and biodiesel-toluene blend compared with diesel at all load.

3.7 Oxides of Nitrogen

The variation in unburned hydrocarbon at various load for distinct blends is shown in Fig.7. NOx is most dangerous emissions in diesel engine which leads environmental pollutions. At all operating condition the NOx emissions are higher for biodiesel B20 than diesel. This is the disadvantage of enforcing biodiesel for commercial application. NOx has a linearly increasing trend with engine load. The cooling effect dominates the high availability of oxygen. At higher loads, richer air fuel mixture is burnt leading to higher temperature and hence forming more NOx. NOx emissions are lowest for diesel. NOx is reducing with increasing the DEE and toluene content. NOx emission of biodiesel-DEE blend is increased by 6.2% and biodiesel-toluene blend is increased by 5.7% compared to diesel. NOx emission 1.9% was decreased with adding DEE and 2.4% was decreased with adding toluene compared to B20. In 5%DEE+B15, it was found that NOX was decreased in a considerable amount.
DEE gives a cooling effect to the cylinder, and hence, the NOX emissions are found to be lesser than the blends in which it is not present. DEE also improves the cetane number which helps in reducing the in cylinder temperature of the engine. The quantity is found to be directly proportional to the cylinder temperature and availability of oxygen in the cylinder [24].

Figure 7 Variation of NOX with Load for Different Blends at CR18

4. Conclusion
The current research work investigates the impact of DEE and toluene additives with dual biodiesel on diesel engine aspect and the consequence were analyzed to biodiesel blend B20 and diesel fuels. The experimental observations indicate the following conclusions.

The diesel engine action with dual biodiesel combination B20 has exhibit lower brake power, brake thermal efficiency and higher specific fuel utilization. CO and HC emissions were lower and CO2 and NOx were higher compared to diesel. The addition of 5% DEE increased 4.7%, 2.6% brake power, and brake thermal efficiency respectively. Brake specific fuel consumption decreased 3.9% compared to B20. Emissions CO, HC and NOx are decreased 6.4%, 2.8% and 1.9% respectively. CO2 increased 1.0% compared to B20. The addition of 5% toluene increased 5.8%, 3.2% brake power, and brake thermal efficiency respectively. Brake specific fuel consumption decreased 5.4% compared to B20. Emissions CO, HC and NOx are decreased 5.0%, 2.1% and 2.4% respectively. CO2 increased 0.7% compared to B20.

Finally it can be concluded that the effect of 5% DEE and 5% toluene additives with dual biodiesel has shown NOx reduction and improved performance and emissions results analyzed to B20 and much inferior to diesel with respect to emissions. DEE and toluene would make favorable additives for dual biodiesel and diesel. This research concludes that the usage of additives to the biodiesel results in improving the combustion, performance and emission reduction.

Acknowledgements
The Authors would like to thank the Department of Mechanical Engineering, BITS Pilani, Dubai Campus for support to this project.

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