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Numerical optimization and experimental investigation of renewable diethyl ether-fueled off-road CI engines for sustainable transportation

M. Gowthama Krishnan*, R. Praveen, V. Pugalendhi***, S. Ram S******
*Department of Mechanical Engineering, Sri Sivasubramaniya Nadar College of Engineering,
Chennai – 603 110, Tamil Nadu, India, gowthamakrishnanm@ssn.edu.in, ORCID: 0000-0002-8742-2112
**Department of Robotics and Automation, Karpaga Vinayaga College of Engineering and Technology,
Chengalpattu – 603 308, Tamil Nadu, India, praveenrajendran5@gmail.com, ORCID: 0000-0002-8832-9665
***Department of Mechanical Engineering, Tagore Engineering College,
Chennai – 600 127, Tamil Nadu, India, pugalmit@gmail.com, ORCID: 0009-0001-3659-8505
****School of Mechanical Engineering, Sathyabama Institute of Science and Technology,
Chennai – 600 119, Tamil Nadu, India, ramprakashnec@gmail.com, ORCID: 0000-0002-7969-2155

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Abstract: Cleaner energy generation on light-duty off-road diesel engines is one of the objectives of this study, which utilizes renewable diethyl ether (DEE) as a replacement for diesel to minimize the reliance on fossil diesel fuel. In an air-cooled single-cylinder diesel engine, various DEE mixes of 5, 10, 15, 20 and 25% were attempted and evaluated under varying loads (0, 25, 50, 75 and 100%) in an effort to enhance the performance and emission characteristics of agriculture diesel engines and lower the environmental effect of harmful emissions. The injection pressure was optimized using computational fluid dynamics (CFD), and performance and emission outcomes were optimized through response surface methodology (RSM) techniques. The experimental results found that brake thermal efficiency and specific fuel consumption were enhanced for a higher proportion of DEE blends under increasing loads. In addition, increasing the engine load decreased CO emissions while increasing carbon dioxide (CO_2), hydrocarbon (HC), and nitrogen oxide (NOx) emissions. Reduced CO, NOx, and HC emissions and increased CO_2 were realized in the blended fuel samples compared to those of pure diesel fuel at increasing DEE percentages. In summary, the utilization of a 15% DEE blend and the optimization of the injection pressure to 210 bar resulted in a notable improvement of 10% in thermal efficiency and a decrease in emissions by 5% when compared to other parameters.
Keywords: Diesel engine, diethyl ether, performance, emission, NOx, CFD

Sürdürülebilir ulaşım için yenilenebilir dietil eter yakıtlı arazi dışı CI motorlarının sayısal optimizasyonu ve deneysel incelenmesi

Özet: Fosil dizel yakıtına bağımlılığı en aza indirmek için dizel yerine yenilenebilir dietil eter (DEE) kullanan bu çalışmanın amaçlarından biri, hafif hizmet arazi dizel motorlarında daha temiz enerji üretimidir. Hava soğutmalı tek silindirli bir dizel motorda, %5, 10, 15, 20 ve 25'lik çeşitli DEE karışımları denenmiş ve değişen yükler altında (%0, 25, 50, 75 ve 100) değerlendirilmiştir. Tarımsal dizel motorların performans ve emisyon özelliklerini azaltarak zararlı emisyonların çevresel etkisini azaltır. Enjeksiyon basıncı, hesaplamalı akışkanlar dinamiği (CFD) kullanılarak optimize edildi ve performans ve emisyon sonuçları, yanıt yüzeyi metodolojisi (RSM) teknikleri aracılığıyla optimize edildi. Deney sonuçları, artan yükler altında daha yüksek oranda DEE karışımı için fren termal verimliliğinin ve spesifik yakıt tüketiminin arttığını buldu. Ayrıca motor yükünün arttırılması CO emisyonlarını azaltırken karbondioksit (CO2), hidrokarbon (HC) ve nitrojen oksit (NOx) emisyonlarını artırdı. Artan DEE yüzdelerinde, saf dizel yakıtla karşılaştırıldığında, harmanlanmış yakıt örneklerinde CO, NOx ve HC emisyonlarında azalma ve CO2 artışı elde edildi. Özetle, %15 DEE karışımının kullanılması ve enjeksiyon basıncının 210 bar'a optimizasyonu, diğer parametrelerle karşılaştırıldığında termal verimlilikte %10'luk kayda değer bir iyileşme ve emisyonlarda %5'lik bir azalma ile sonuçlandı.
Anahtar Kelimeler: Dizel motor, dietil eter, performans, emisyon, NOx, CFD

Nomenclature

BTE-Brake thermal efficiency
BSFC -brake specific fuel consumption
CO_2- Carbon dioxide
CO-Carbon monoxide
CI-Compression Ignition
CFD-Computational fluid dynamics
DEE- Diethyl ether
HC- Hydrocarbon
ICEs -Internal combustion engines
NOx- Nitrogen oxide
RSM - Response surface methodology
SI-Spark Ignition
WHO- World Health Organization
0% DEE- 100% diesel and 0% diethyl ether
5% DEE- 95% diesel and 5% diethyl ether
10% DEE-90% diesel and 10% diethyl ether
15% DEE-85% diesel and 15% diethyl ether
20% DEE-80% diesel and 20% diethyl ether
25% DEE-75% diesel and 25% diethyl ether

INTRODUCTION

Internal combustion engines (ICEs) are significant prime movers expected to play a significant role in the transportation industry for the foreseeable future. IC engines rely heavily on fossil fuels for power. Heavy reliance on fossil fuels boosted both greenhouse gas emissions and fuel demand. In addition, high industrial and transportation demands are driving up the price of and scarcity of fossil fuels. To minimize fossil fuel utilization for IC engines in the near future, they must use cleaner and alternative fuels. Consequently, the necessity for alternative fuels and their quality enhancement should be explored (Martin et al. 2020). Furthermore, according to the WHO reports, nine out of the ten most polluted cities in the world are in India. By 2024, the nation anticipated reducing air pollution levels by 20 to 30% in 100 major cities (Cristian 2018).

Two of the largest markets for petroleum products are the transportation industry and the farming or agriculture sector. Conventional fossil-based diesel fuel is widely used to power diesel engines in the automobile and agricultural sectors. The necessity of a diesel engine is higher since the thermal efficiency, fuel economy, and endurance limit are higher than gasoline engines. As a result, diesel engines are widely adopted in transport, electricity power generation, and heavy industrial machinery and agriculture sectors. In India's agricultural industry, diesel fuel tractors, farm equipment, and irrigation pump set depend on diesel fuel (Agarwal, Avinash Kumar and Krishn Chandra 2022a; 2022b). However, the increased usage of diesel fuel contributes to harmful high soot and NOx emissions because of the fuel-rich zones from fuel spray and high combustion temperatures from the high compression ratio (Emaish et al. 2021). However, further efforts will be needed to reduce harmful pollution from diesel combustion processes by decreasing nitrogen oxides and particulate matter emissions.

Emission control strategies and enhancing the fuel characteristics like fuel volatility, diminishing the fuel's aromatic and sulfur content, and augmenting the cetane number could be better options to mitigate these emissions. From these points of view, exploring potential alternate fuel sources is typically beneficial, i.e., using oxygenated renewable additives (Mofijur et al. 2015). There is widespread availability of different oxygenated sources; among them, biodiesel, alcohols and ethers are prominent oxygenated fuel sources. Alcohols such as ethanol, methanol, butanol, pentanol, and ethers such as dimethyl, diethyl, dibutyl, and dimethyl carbonate (Praveen et al 2014a; 2014b; Sezer, Ismet 2019; Gainey et al 2021) have been investigated by several studies as oxygenated additives in diesel, biodiesel, and diesel-biodiesel blends (Negi, Himani and Raj Kumar Singh 2020).

Alcohol is primarily used in SI engines due to its superior octane rating, and these days alcohol is also considered a blended fuel for diesel engines (Goktas et al. 2021). However, the usage of alcohol in diesel engines suffers from cold starting issues, and lower calorific values of alcohol affect the performance of the engine. In addition, ethanol and methanol as a binary and ternary blend for diesel cause immiscibility (above 10 % by volume), hygroscopic and phase separation problems under higher alcohol proportion (Nanthagopal et al. 2020).

In this context, ethers are another oxygenated option in which among different ethers the DEE is a renewable oxygenated additive or fuel produced from ethanol using a dehydration process (Jawre et al. 2016; Dinesha et al. 2019). DEE offers numerous desirable characteristics for diesel-powered engines as an alternate fuel, i.e., high oxygen content (21.6%), enhanced miscibility, reasonable energy density, high cetane number, non-corrosive, increased flammability limits and low auto-ignition temperature (Agarwal et al. 2022). Furthermore, the greater H/C ratio and fewer C-C bonds of DEE as a diesel fuel addition resulted in less soot production (Nanthagopal et al. 2019).

Gorski and Przedlacki (2014) analyzed the physicochemical properties of diesel fuel containing DEE. They noticed that blends were stable at temperatures below 0°C, that the cold filter pour point decreased, and that the miscibility of the blend was improved throughout a range of temperatures. In addition, fuel injectors were not affected by the modest reduction in lubricity. However, the viscosity decreases, and if the blend is tested above 20% by volume, it creates vapour locks and deteriorates performance. As well, Iranmanesh et al. (2008) reported that DEE as an additive (2,5 and 10% volume) in diesel fuel improved the viscosity, cetane number, flash point and fuel volatility.

Ibrahim (2016) tested a single-cylinder diesel engine with 5, 10 and 15% DEE blends and found that 15% DEE improved the brake thermal efficiency by 7.2% and abridged the BSFC by 6.7% in comparison to diesel fuel. However, the combustion stability was slightly affected when the blends were more than 20%. In another study, Subramanian et al. (2002) investigated DEE (5,10 and 15% by weight) together with water-diesel emulsion and reported improved performance and lower NOx, smoke and increased HC and CO emissions. Ismet Sezer (2018) reviewed the effect of DEE on NOx emissions and reported that adding DEE to diesel and biodiesel blends reduces the NOx emissions owing to the higher cetane number and latent vaporization, and lower heating value.

Similarly, Lee and Kim (2017) studied the maximum concentration of DEE (10, 25 and 50%) in diesel fuel, compared the results with diesel fuel, and found lower CO, HC, and particular emissions. However, DEE blends suffered from higher NOx emissions because of reduced ignition delay and inborn oxygen content. Rakopoulos et al. (2013) investigated the combustion behaviour of diethyl ether in diesel fuel. They reported no cyclic variations, i.e., stable operation of engine operated with DEE blends up to 24% relative to diesel fuel. Moreover, the maximum pressure rate was lower (~ 3 bar/deg), whereas it is ~4.3 bar/degree for diesel fuel at a rated (5.37 bar BMEP) load.

Researchers also tested diethyl ether as an additive for diesel-biodiesel blended fuels. Ali et al. (2016) showed that DEE as an additive (2, 4, 6 and 8% by volume) for diesel-biodiesel blends (B30) deteriorated the heating value of B30 and increased the cyclic variability at increased DEE proportion. Carvalho et al. (2020) found that the addition of 5% DEE in ternary blends of diesel-ethanol-biodiesel under different loads (8, 16 and 24 kW) increased the HC emissions and decreased the NOx and smoke emissions at all loads. In an investigation on DEE (Ibrahim 2018), 5% of DEE in a diesel-biodiesel blend showed improved BTE and BSFC; however, the performance (efficiency and fuel consumption) was affected when the DEE blend increased to 10% owing to the latent heat of vaporization and lower calorific value of DEE. Prabakaran et al. (2022) reported that for diesel-biodiesel-DEE blends under all load conditions (0 to 100%), the NOx emissions were increased by 11.6, 16.2 and 18.7% at increased DEE content (5,7.5 and 10% by volume). The increased oxygen content of DEE and biodiesel in ternary blends was the primary reason for NOx formation. A similar increase in NOx emission was reported by Reddy et al. (2022) for DEE-biodiesel blends. However, other emissions (HC, CO and smoke) were decreased with improved performance due to better oxidation and combustion. Similar reduction in HC and CO was also reported in the studies of different biodiesel fuel with DEE blends (Rami Reddy et al. 2022; Dinesha et al. 2019).

Literature indicates that biodiesel blends and ternary blends of diesel-DEE-biodiesel reported higher NOx emissions at rated loads. In addition, the alcohols as a diesel blend suffered from phase separation problems at increased alcohol concentration. Hence, oxygenated DEE is chosen as an alternative fuel in this work. Literature is scarce on the combined effects of diethyl ether-diesel and response surface approaches on the performance and emissions of a compression ignition engine. The novelty of this work comprises a numerical and experimental approach to identifying the optimum usage of renewable diethyl ether across distinct load circumstances of agricultural diesel engines in order to reduce diesel utilization and CO_2 emission and enhance performance and other emission characteristics. Consequently, the objective of the study is to examine the optimal injection pressure for tested DEE blends of 0 to 25% using CFD and investigate the different DEE blends in diesel fuel operating under diverse loads of 0 to 100%. Finally, the performance and emission outcomes of DEE blends are compared with conventional diesel fuel.

MATERIALS and METHOD

CFD modelling

Controlling the fuel injection conditions is one way to influence the combustion parameters. This study employs computational fluid dynamics (CFD) to investigate the combination of diesel and oxygenated fuel on spray properties under high-pressure fuel injection. Cross-sectioned model dimensions of the injector and closed chamber are shown in Figure 1. The injector had six orifice holes of 0.04 mm diameter with an equal spacing of 60 degrees. The injection pressure was varied between 200, 205, and 210 bars, while the ambient pressure and temperature were kept constant at 1 atm and 305K. The mixture of 75% diesel and 25% diethyl ether blend fuel was considered for all simulation trials. Table 1 describes the properties and boundary conditions of the chamber and injector. The properties of diesel-diethyl ether blends are given in Table 2. The spray characteristics of diesel-diethyl ether blends were studied using CFD. This includes spray angle, penetration length, and air-fuel mixture parameters such as pressure, velocity and viscosity patterns.

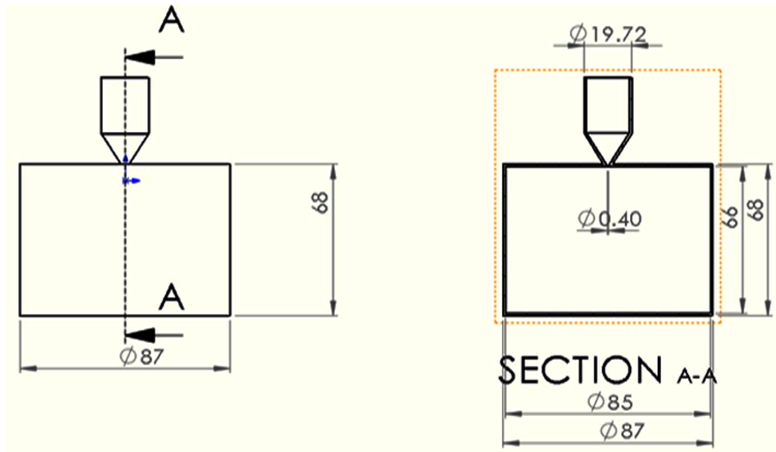

Figure 1. Dimensional cross-section of the CFD model: Cylindrical chamber and fuel injector

Table 1. Properties and boundary conditions of cylindrical chamber and injector

Material Specification	Aluminium
Ambient pressure	1 bar
Ambient temperature	305K
Injection pressure	200 bar, 205 bar 210 bar
Boundary condition	
(i) Inlet	fuel injector
(ii) Boundary	wall
(iii)Interior	Compressed air

Table 2. Fuel properties of diesel and diethyl ether (DEE)

Fuel Properties	Diesel	Diethyl ether
Density at 20°C (kg/m^3)	820	713.4
Boiling point (°C)	240-360	34.6
Latent Heat of vaporization (kJ/kg)	250-290	376
Flash point (°C)	52-96	-45
Auto ignition temperature (°C)	260	160
Calorific Value at 20°C (MJ/kg)	44.9	33.892
Stoichiometric A/F ratio	14.4	11.2
Octane number	-	92
Cetane number	50	125
Kinematic Viscosity (cS)	0.223	0.224

Experimental test facilities and methods

Experimentation was conducted using a single-cylinder, air-cooled research engine. The maximum power output of the test engine is 4.4 kW at a constant speed of 1,500 rpm. Table 3 details the test engine's specifications. Figure 2 depicts a pictorial representation of the research engine. An electrical dynamometer was used to apply load by varying the field current. To monitor airflow, a manometer connected to a large tank was attached to the engine. Using a burette and stopwatch, the flow rate of fuel was measured volumetrically. A crank angle encoder (365C Indi Advanced) manufactured by AVL is installed on the camshaft of the engine. The test apparatus is outfitted with AVL software to generate an operational performance measurement.

Table 3. Specification of research engine

Engine type	Four stroke diesel engine
Bore	87.5 mm
Stroke	110 mm
Swept volume	661.5 cc
Injection timing	23° b TDC
Nozzle opening pressure	220 bar
Rated output	4.4 kW
Rated speed	1500 rpm
Compression ratio	17.5:1

Initially, conventional diesel fuel was used to obtain baseline data under fixed speeds and different load conditions (25–100%). Secondly, the diesel fuel was blended with oxygenated diethyl ether diesel. The amount of oxygenated diethyl ether in diesel was then varied between 5, 10, 15, 20, and 25%. Based on CFD analysis, the optimal injection pressure was determined. Then the prepared blends were tested, and their performance and emission parameters were investigated and compared with those of baseline diesel fuel. The Bridge five gas exhaust emissions analyzer was used to measure exhaust pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), hydrocarbons (HC), and oxygen (O_2).

Table 4. Accuracy and error (%) of measuring instruments

Parameters	Accuracy	Error (%)
CO	± 0.01%	± 0.1
CO_2	± 0.3 %	± 1.5
HC	± 8 ppm	± 0.2
NOx	± 5 ppm	± 0.1

An investigation of the experimental setup's uncertainty was required to reduce error and confirm the experiment's accuracy. Hence, the uncertainty analysis was performed for all the tested conditions and were calculated based on the equation (1) given below.

$$\Delta U = \sqrt{\left\{\left(\frac{\partial U}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial U}{\partial x_2}\Delta x_2\right)^2 + \left(\frac{\partial U}{\partial x_3}\Delta x_3\right)^2 + \cdots + \left(\frac{\partial U}{\partial x_n}\Delta x_n\right)^2\right\}} \quad (1)$$

Where, U denoted the overall uncertainty. $x_1, x_{2,} x_3 \ldots x_n$ are independent variables and $\Delta x_1, \Delta x_2, \Delta x_{n1}$ are the errors. Table. 4 represent an accuracy and error percentage of measuring instruments and Table. 5 represent the overall uncertainties.

Table 5. Overall percentage of uncertainty

Parameters	Uncertainty (%)
Shaft power	0.83
Fuel consumption	0.31
BTE	1.05
BSFC	0.95
CO	1.23
HC	1.35
CO_2	1.12
NO_x	0.80

Results and discussion

This section explains the spray characteristics, performance, and emission parameters of diesel and oxygenated blended fuel (i.e., diethyl ether) in varying amounts.

Numerical spray characteristics

The numerical spray characteristics such as pressure, velocity, viscosity, spray cone length and spray cone angle of diesel and diethyl ether blends are discussed in this section.

The change in pressure, velocity, and viscosity distribution of diesel and DEE blends at varied fuel injection pressures (i.e., 200, 205, and 210 bar) are shown in Figures 3–5. In the case of fuel injection pressures of 200 and 205, a partial amount of vaporization and atomization of fuel occurred. But when fuel was injected at 210, the pressure was spread evenly across the cylindrical chamber, and the fuel was completely atomized. This is depicted in Figures 3 (a-c). The change in velocity distribution of fuel injection pressures of 200, 205, and 210 bars is shown in Figures 4 (a–c). Upon increasing the injection pressure, the velocity distribution of fuel decreases. When the injection pressure was low and there was some semi-liquid fuel, the peak velocity of the spray gathered in the middle portion. Figures 5 (a-c) depict the variation in the viscosity pattern of diesel-diethyl ether fuel blends at various injection pressures. In the case of low injection pressure (200 bar), the viscosity of fuel was higher compared to high injection pressure (210 bar). The spray cone length and cone angle were similar in all cases. However, the uniform distribution of fuel in a cylindrical chamber with a swirl flow pattern was achieved in the case of 210 bar injection pressure, and this phenomenon was absent in the case of 200 and 205 bar injection pressure. Based on these observations, it shows clear evidence that the complete vaporization, atomization, and uniform distribution of fuel blends were achieved in the case of 210 bar injection pressure. Hence, this optimized injection pressure was considered for all the experimental test trials.

Performance Characteristics

The performance characteristics like BTE, BSFC, mechanical efficiency and exhaust gas temperature of diesel and DEE blends are discussed in this section.

The variations in BTE of diesel and DEE blends under diverse loads are shown in Figure 6. The BTE rises as the engine load rises because, with increasing load levels, the fuel required to match is higher to meet the operating load and effective power produced is higher results in increased BTE. From Figure 6, it can be observed that for all load levels, increasing the DEE concentration from 5 to 25% in diesel fuel improved the BTE. This is because the inclusion of DEE increased combustion efficiency due to the inherent oxygen content and higher cetane number (Agarwal et al. 2022a), hence increasing the BTE of diesel-DEE blends.

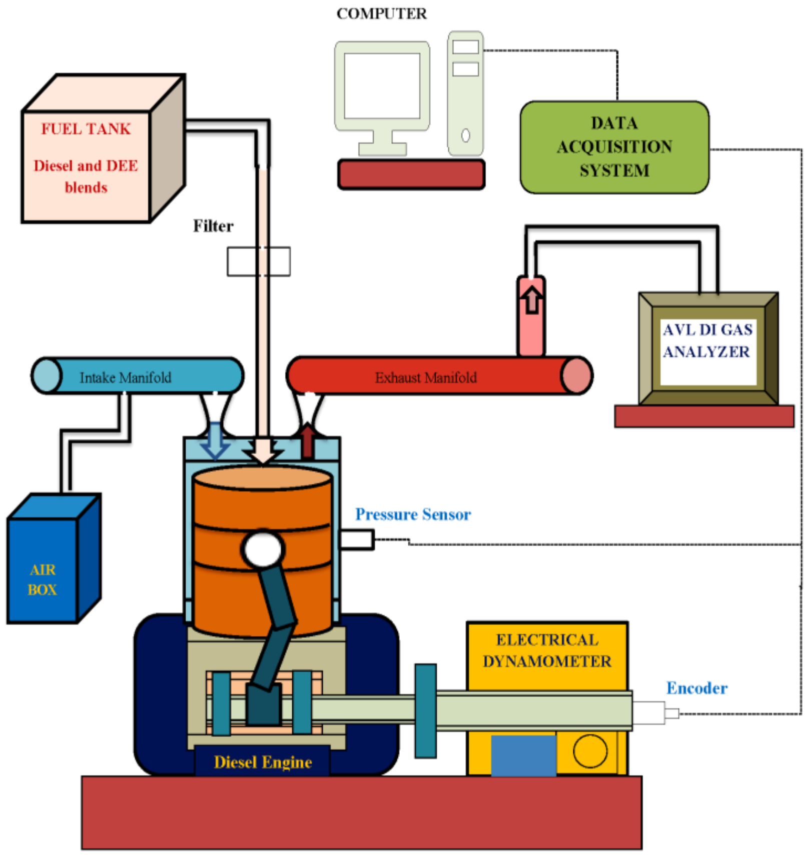

Figure 2. Schematic of research engine test setup

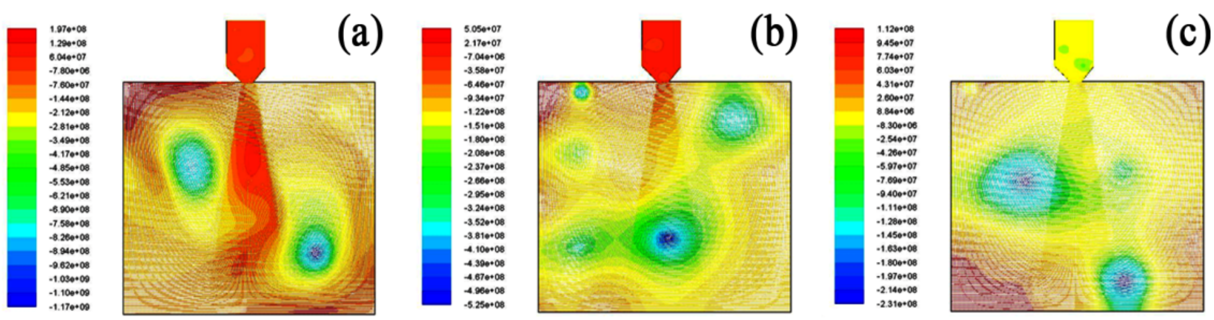

Figure 3. Change in pressure distribution of diesel-diethyl ether fuel blends at varied injector pressure (a) 200 bar (b) 205 bar and (c) 210 bar

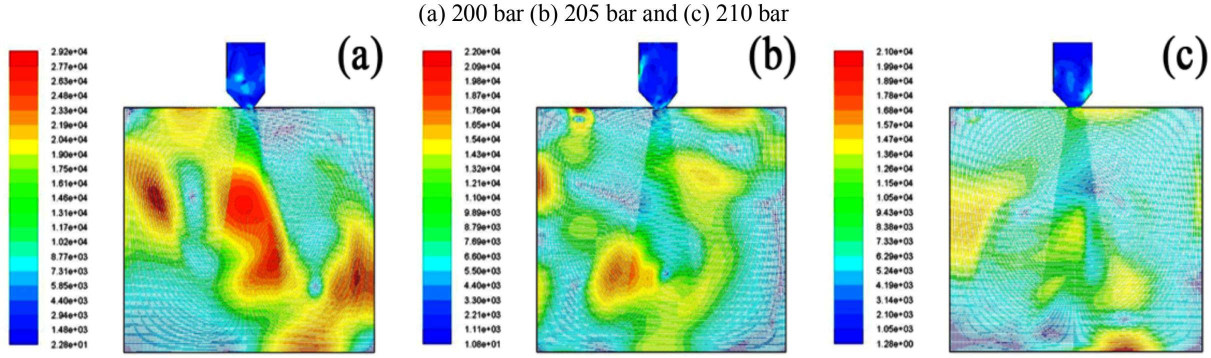

Figure 4. Change in velocity distribution of diesel-diethyl ether fuel blends at varied injector pressure (a) 200 bar (b) 205 bar and (c) 210 bar

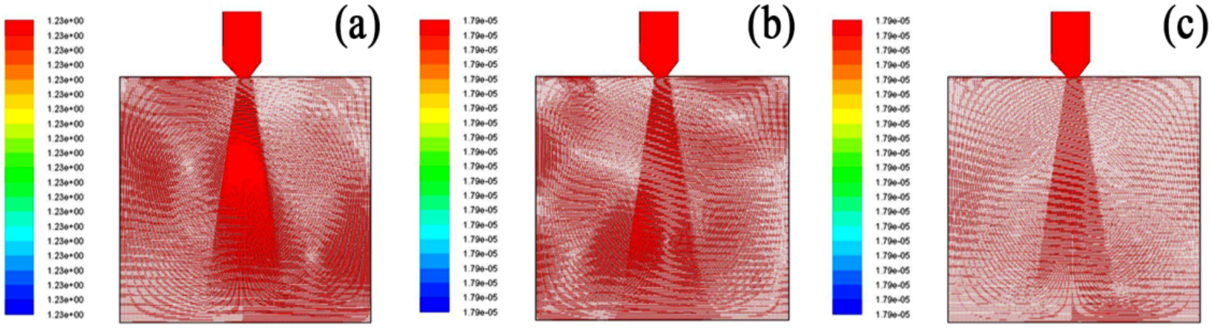

Figure 5. Change in viscosity distribution of diesel-diethyl ether fuel blends at varied injector pressure (a) 200 bar (b) 205 bar and (c) 210 bar

Furthermore, the interfacial tension between two or more interacting immiscible liquids helped fuel atomization, improving diesel combustion. Among the tested fuels, the maximum BTE is observed for 25% DEE at 75 and 100% rated loads. This is because, at increased DEE concentration, the higher volatile characteristics and reduced viscosity of DEE improve air-fuel mixing, which promotes combustion and facilitates an increase in BTE (Ibrahim 2016).

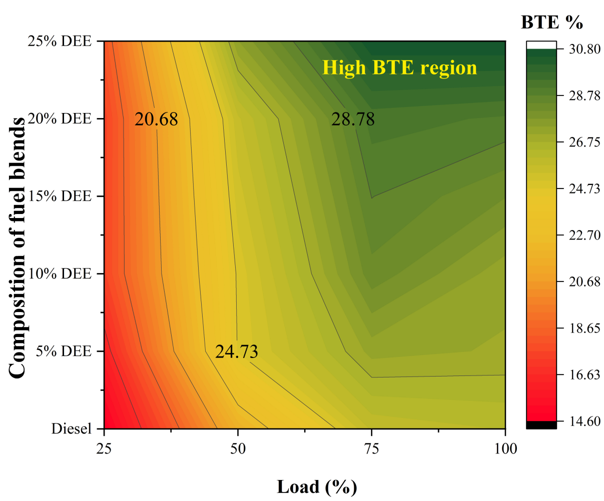

Figure 6. Comparison of BTE of diesel and DEE blends

The variations in brake specific fuel consumption (BSFC) of diesel and DEE blends under varied loads are shown in Figure 7. From Figure 7, it can be seen that the increasing DEE proportion decreases the BSFC compared to pure diesel fuel for all load points. Therefore, the drop in BSFC with increasing load could be attributable to the greater availability of fuel oxygen.

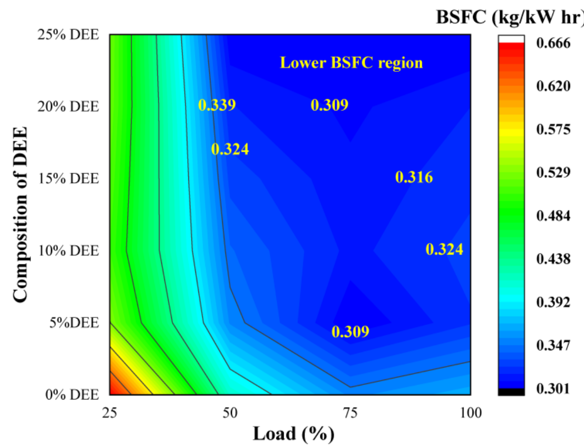

Figure 7. Comparison of BSFC of diesel and DEE blends

Figure 8 represents the improvement scale of mechanical efficiency of DEE blends under different loads. It is observed from Figure 8 that the increase in the proportion of DEE from 0 to 25% in diesel improved the mechanical efficiency under all loads. It could be due to the inherent oxygen content of DEE that promotes combustion and increases power output.

Improvement Scale

Load (%)	Diesel	5% DEE	10% DEE	15% DEE	20% DEE	25% DEE
25	20.74	24	24.96	25.13	25.3	26.1
50	41.86	44	44.97	44.925	44.88	45.12
75	57.28	61.7	60.77	61.45	62.13	63.11
100	69.98	75.52	75.91	76.03	76.15	77.23

Figure 8. Comparison of mechanical efficiency of diesel and DEE blends

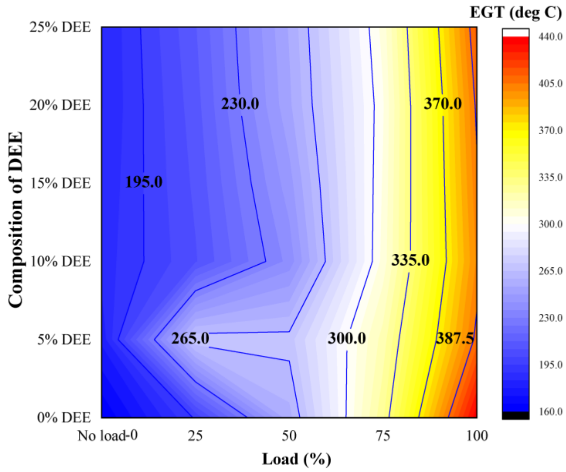

Figure 9. Comparison of EGT of diesel and DEE blends

Figure 9 depicts the variation in exhaust gas temperature (EGT) of DEE blends under different loads. From Figure 9, it is observed that the EGT of the diethyl ether blend is lesser than the conventional diesel under medium to high loads (50 to100%). This reduction in exhaust gas temperature of DEE blends could be accredited to the presence of lower calorific value fuel of DEE than diesel fuel.

Emission Characteristics

This section discusses the effect of DEE addition in diesel fuel and its various engine exhaust emission parameters like carbon monoxide, carbon dioxide, oxides of nitrogen, and hydrocarbon.

CO emissions in diesel engines are mainly due to inefficient fuel combustion in an oxygen-deficient environment. Figure 10 depicts the variation in Carbon Monoxide (CO) emissions of DEE blends under different loads. Figure 10 shows that CO emissions were decreased with a rise in engine load level. This is because low combustion temperature at load loads contributes to higher CO emissions. However, the scenario is different at high load conditions because the in-cylinder environment is high enough to oxidize carbon monoxide, resulting in reduced CO level than low load conditions.

It can be seen from Figure 10 that CO emissions were lower for increased DEE concentration from 5 to 15% at all load conditions. The inherent oxygen content of DEE promotes CO oxidation, resulting in lower CO emissions compared to conventional diesel fuel. However, Fig.10 shows that CO emissions are elevated at lower loads for all DEE blends compared to high loads. This could be accredited to the latent heat of evaporation of DEE producing a cooling effect that affects the oxidation process resulting in a considerable increase in CO emissions. The fuel-bound oxygen in DEE blends is offset by the latent heat of vaporization of DEE fuel (Sezer 2019). Overall, 10% DEE exhibits lower CO levels among tested blends at all load conditions.

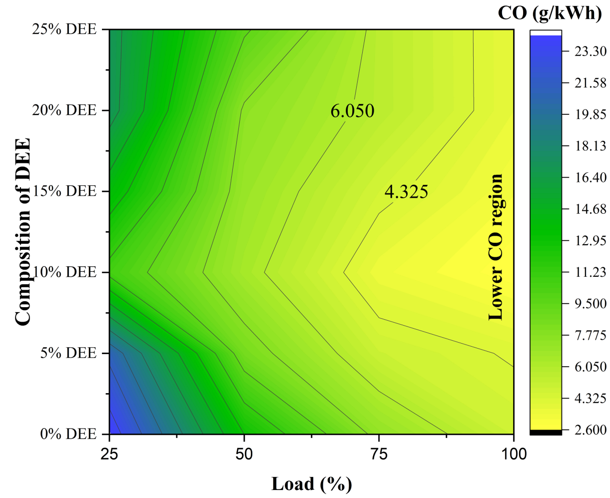

Figure 10. Comparison of CO emissions of DEE blends and diesel under different loads

In general, HC emissions from diesel engines are influenced by fuel-air mixing and the physical properties of the fuel. During diesel engine combustion, HC emission mainly forms due to partial or un-burnt fuel. This could be due to flame quenching near cylinder walls, over mixing or under mixing of air-fuel mixtures. Figure 11 represents the variation in hydrocarbon (HC) emissions of DEE blends under different loads. It can be seen from Figure 11 that HC emissions were decreased for all the tested DEE blends compared to diesel fuel up to part loads and identical values and slight variations at high loads. It could be attributed to the cetane number of DEE, which is higher than diesel, resulting in shorter ignition delay and contributing to enhanced combustion (Agarwal et al. 2022).

Furthermore, the oxygen content of DEE oxidizes the HC leading to a lower HC level. Increasing the DEE concentration in diesel fuel decreases the HC up to 10% and then increases at 15 to 25% DEE. Because the higher concentration of DEE produces a cooling effect which affects the HC oxidation. Similar studies (Agarwal et al. 2022a; Dinesha et al. 2019; Iranmanesh et al. 2008 and Lee and Tae 2017) in the literature also reported higher HC with increased DEE. Overall, 10% DEE exhibits a lower HC level among tested blends at all load conditions.

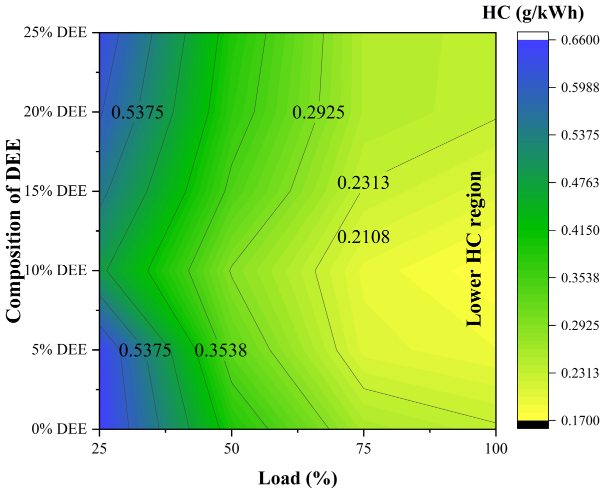

Figure 11. Comparison of HC emission of DEE blends and diesel under different loads

Generally, the more fuel the engine burns, the more carbon dioxide is emitted into the atmosphere. Figure 12 depicts the variation in carbon dioxide (CO_2) emissions of DEE blends under different loads. Figure 12 shows that CO_2 emissions increased with the increase in engine load from no load to full load conditions. Since better in-cylinder environment temperature occurs at elevated loads, enhanced combustion causes greater CO_2 level than lower load levels. As the CO_2 level increases, there is a betterment of combustion. Figure 12 indicates that CO_2 emissions were more significant for all the DEE blends (5 to 15%) under all load conditions because the fuel-bound oxygen of DEE contributes to more efficient combustion, resulting in higher CO_2 emissions than conventional diesel fuel.

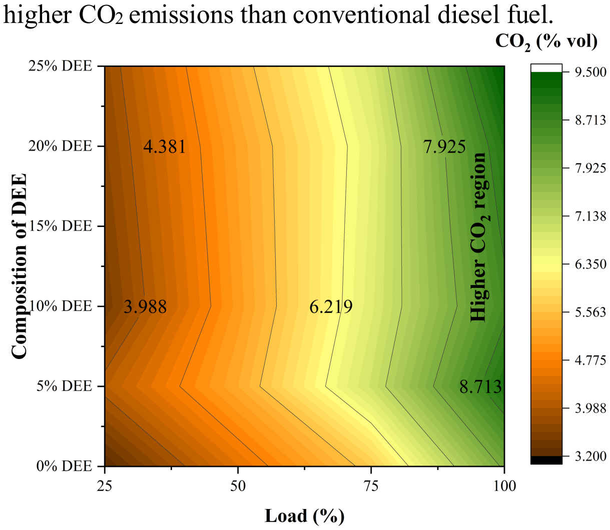

Figure 12. Comparison of CO_2 emission of DEE blends and diesel under different loads

In general, NOx formation in diesel engines is influenced by the duration of combustion, oxygen availability, temperature, pressure and increased compression ratios. In the diesel engine, combustion occurs at higher temperatures, causing nitrogen in the air to react with oxygen to form NOx emissions. Furthermore, the spray characteristics, oxygen concentration and adiabatic temperature of fuel blends influenced the exhaust NOx emissions.

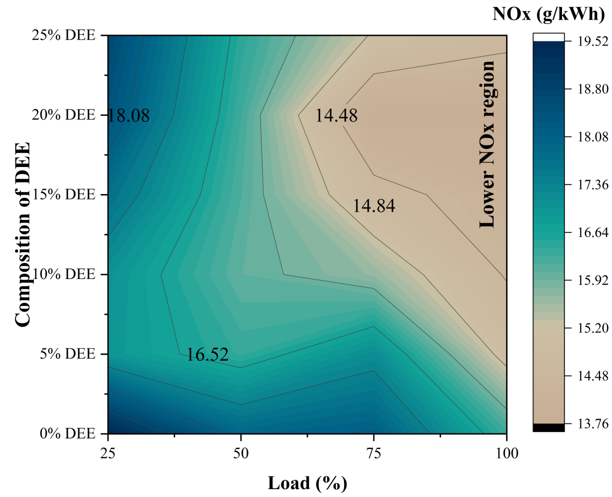

Figure 13. Comparison of NO_x emission of DEE blends and diesel under different loads

NOx emission variations of DEE blends under different loads are shown in Figure 13. In general, the thermal NOx effect at increasing loads increasing the combustion temperature led to increased NOx formation level. However, From Figure 13, it is observed that increasing the load from 0 to 100% load decreases the NOx emissions. This could be due to lower NOx emissions per unit brake power output than lower loads. Figure 13 shows that under all load levels, NOx emission of DEE blends is decreased with an increase in blend level from 0 to 15%, and it is also lower than baseline diesel fuel. This could be accredited to the addition of DEE to diesel fuel in which diethyl ether diminishes the combustion temperature since the latent heat of vaporization of DEE is higher than diesel which is beneficial in reducing the combustion temperature. This decreasing NOx trend with increased DEE concentration was corroborated with similar diesel-DEE blend studies (Agarwal et al. 2022a; Sezer 2018; Ibrahim 2018; Firew et al. 2016).

Response surface methodology (RSM) method

In general, there will be a greater number of experiments carried out in order to validate the reproducibility and accuracy of the findings. To reduce the number of experiments, an attempt was made to predict engine performance (BTE, BSFC, and mechanical efficiency) and exhaust gas emissions (CO, HC, and NOx) as a function of percentage of engine load and percentage of DEE blends using response surface methodology. Using this method, 3D surface plots (Figures 14 and 15) between the aforementioned variables were created with a fit efficiency between 96% and 100%.

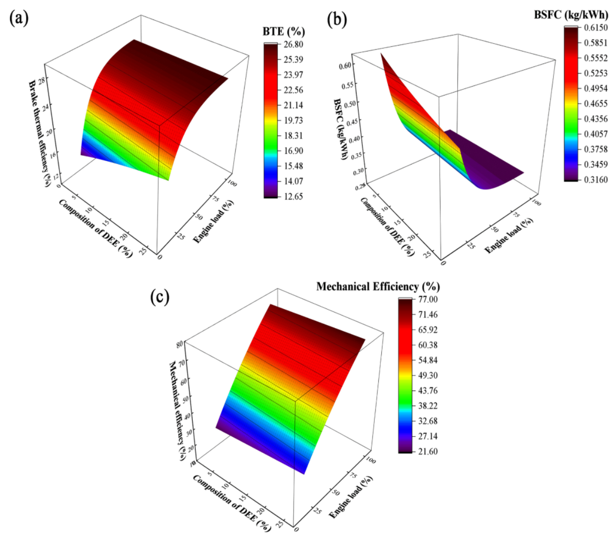

Figure 14. Response surface plots of performance characteristics of DEE blends (a) BTE (b) BSFC and (c) Mechanical efficiency

From Figure 14, it is clearly indicated that BTE and mechanical efficiency were higher and BSEC was lower when an engine runs with 25% DEE blends at peak load conditions compared to neat diesel. Similarly, exhaust gas emissions (CO, HC, and NOx) were lower compared to neat diesel, as shown in Figure 15. An optimized injection pressure of 210 bar and 15% DEE blends show a significant rise in engine performance as well as reduced emissions.

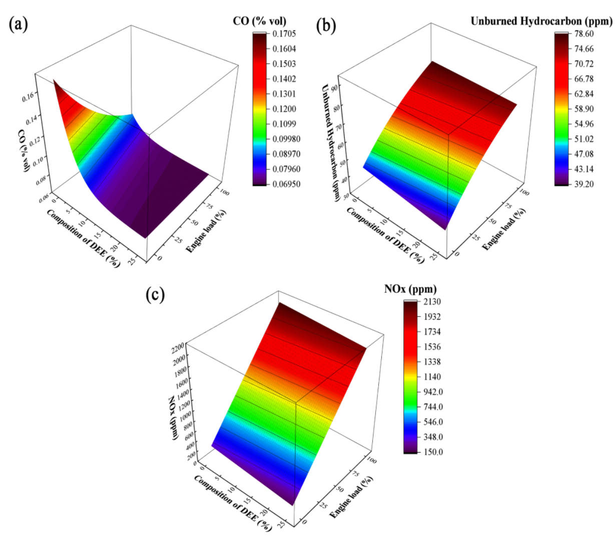

Figure 15. Response surface plots of emission characteristics of DEE blends (a) CO (b) HC and (c) NOx

A polynomial 2D exponential fit equation was generated using the fit surface, and the same is given in Eq. 2. The surface equation was used to predict engine performance (BTE, BSFC, and mechanical efficiency) and exhaust gas emissions (CO, HC, and NOx) for different engine loads (%) and DEE blend compositions (%). Using this expression, one can determine the engine parameters with respect to the engine load (%) and composition of DEE blends.

$$Z = Z_o + \left\{B\left(\exp\left(\frac{-X}{C}\right)\right)\left(\exp\left(\frac{-Y}{D}\right)\right)\right\} \tag{2}$$

Percentage variations comparison of DEE blends with baseline diesel

The Percentage variations of Performance and emissions of DEE blends compared to pure diesel fuel, as given in Table 6. BTE is highest at a 25% DEE for all loads, having 25.9% improvement 25.9% over pure Diesel fuel. When employing 20% DEE at varied loads, NOx shows a reduction of up to 24% than diesel. DEE at 10% shows significant reduction of HC and CO among other blends across loads. Reduced by a maximum of 26.9% at 100% for HC and 64.8% at 25% load for CO.

Table 6. Percentage variations of Performance and emissions of DEE blends compared to pure diesel fuel (-) denotes percentage decrement

Performance & emission parameters	Load (%)	Fuel blends				
		5% DEE	10% DEE	15% DEE	20% DEE	25% DEE
BTE (%)	25	10.7	19.9	19.6	19.3	23.7
	50	13.8	14.1	16.0	17.9	25.9
	75	5.5	9.7	11.5	13.4	19.1
	100	3.6	4.3	7.8	11.3	18.0
NOx (g/kWh)	25	-13.1	-12.7	-9.2	-5.7	-4.2
	50	-8.7	-10.5	-9.9	-9.2	-8.2
	75	-5.3	-13.6	-18.8	-24.0	-16.4
	100	-8.3	-11.7	-13.5	-15.4	-10.3
HC (g/kWh)	25	-1.5	-26.1	-16.4	-8.3	-3.6
	50	-16.1	-25.9	-12.2	-4.0	0.0
	75	-20.0	-23.5	-11.2	-3.0	-3.2
	100	-18.7	-26.9	-13.1	-0.4	0.5
CO (g/kWh)	25	-30.3	-64.8	-54.2	-43.6	-43.6
	50	-34.1	-49.9	-45.7	-41.6	-25.0
	75	-32.6	-51.5	-36.9	-22.4	-22.5
	100	-12.9	-45.0	-33.8	-22.5	-22.7

Conclusions

This study evaluated an air-cooled agricultural diesel engine with various DEE-to-diesel mixtures. The conclusions can be summarized as follows:

- The 210-bar injection pressure was found to be optimal for the DEE blends.
- The higher proportion of DEE blends under increasing loads enhanced the brake thermal efficiency and specific fuel consumption

compared to diesel fuel. The maximum BTE was noted for the 25% DEE blends at rated loads.

- Increasing DEE blends improved the mechanical efficiency at all load levels.
- For all load levels, all the DEE percentages lowered CO, NOx, and HC emissions compared to pure diesel fuel. Expect the HC emission of 25% DEE blend.
- By increasing the DEE blend in diesel fuel by up to 20%, NOx and CO emissions are reduced. In contrast, HC lowers the DEE blend up to 15%.
- Among the assessed mixtures, when evaluating the balance between brake thermal efficiency (BTE) and emissions, the use of a 15% DEE blend and optimizing the injection pressure to 210 bar led to a significant 10% enhancement in thermal efficiency and a 5% reduction in emissions.

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