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Research Article

Performance and engine exhaust study of a CI engine in dual fuel mode using diethyl ether as cetane enhancer additive

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Abstract

In this experiment, emission and performance analysis were conducted on a compression ignition (CI) engine operating with a blend of Karanja methyl ester and diesel as the pilot fuel. Diethyl ether (DEE) was used as a cetane enhancer to improve the brake thermal efficiency (BTE) of dual fuel (DF) engines. Producer gas (PG) was utilized to maximize diesel savings. The results show that BTE decreased in DF runs while using PG. However, when a 5% volume fraction of DEE was mixed with the selected pilot fuels, it led to an improvement in BTE during the DF run. The emission curves also reveal the positive impact of DEE on DF engine performance. Further investigation showed that a 10% volume fraction of Karanja methyl ester (B10) blended with diesel, when additionally mixed with 5% volume of DEE (referred to as 5DEE), achieved a BTE of 26% during DF mode operation with PG. In comparison, B10+PG, Diesel+PG, and Diesel+5DEE+PG reached BTEs of 23.75%, 24.2%, and 27.2%, respectively. Among these combinations, B10+5DEE+PG showed the highest reduction in smoke opacity (51.3%) and nitric oxide (54%) emissions during DF operation compared to the base results. Additionally, B10+5DEE+PG exhibited the lowest increase in hydrocarbon emissions (35.4%) compared to other DF operation combinations.

Keywords

Diesel, Diethyl ether, Emissions, Performance, Producer gas.

1.Introduction

The advancement in technologies and the linked cumulative pollution have severely threatened the health and eco-friendliness of the environment. Further, fossil fuel consumption is increasing daily, emerging as a critical setback, especially for a developing country like India. With the intensifying requirement and growing power sectors worldwide, conventional sources are decaying at a rising rate, forcing researchers to emphasize alternative fuels [1]. Emissions from traditional fossil fuel consumption are causing serious problems in terms of global warming and climate change. Fossil fuels were generally predicted to get exhausted very soon, owing to the rapid consumption [2]. Diesel engines are considered as the prime mover in most of the areas such as agriculture, transportation, and construction sectors and it emits particulate matter, carbon dioxide (CO_2), oxides of nitrogen (NO_x), and other hazardous gases. Diesel engines are also a substantial contributor to global warming caused due to greenhouse gas emissions [3]. Hence, the researchers need to rethink the above said challenges and focus their research on alternative fuels that must be renewable and reduce the hazardous emissions from compression ignition (CI) engines [4]. Alternative fuels, such as natural gases, biofuels, producer gas (PG), biogas, and hydrogen, are generated from renewable energy sources that are extensively available within the environment, replacing conventional fossil fuels [5]. As a result, it positively impacts controlling environmental pollution and global warming [6]. In addition, the above alternative fuels can be generated from a wide range of renewable sources such as municipal waste and biological waste which is otherwise being discarded into the environment.

There is a wide range of biomass feedstock readily accessible for harvesting energy in the form of solid, liquid, and gaseous fuels that are used in thermal power production approaches. On this basis, a wide range of processes exist to extract energy from waste

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biomass, like trans-esterification, gasification, anaerobic digestion, pyrolysis etc. Various studies concluded that the use of vegetable oil and its esters can be considered a viable alternative to diesel fuel and does not require any engine modifications to attain the same degree of performance. In most cases, biodiesel synthesized from feedstocks such as Jatropha and Karanja are blended with diesel to be used in CI engines [7]. Most of the researchers are working on ether group fuels which contain molecular oxygen that can reduce the emissions from the CI engines caused due to partial combustion. At the same time, ether-based biofuels can effectively prevent the problems of popping and cold start difficulties because of their high cetane number. Such attributes make ether group fuels promising alternatives or additives to diesel fuels [8–10].

Oxygenates like methanol, ethanol, n-butanol, diethyl ether (DEE), di-methyl ether, and di-methyl carbonate are commonly used as additives to enhance the cetane number. Notably, DEE, which is derived from dehydrated ethanol, is particularly suitable for diesel engines due to its higher cetane number of 125 [11]. It was reported that oxygenated fuel additives when mixed with fossil fuels helps to lower the soot formation [12]. The utilization of renewable biomass-derived gaseous fuel in conjunction with liquid pilot fuel, operating in a dual fuel (DF) mode, can be considered as a promising solution to address the energy crisis [2]. DF mode run provides interoperability in operational mode based on the need for gaseous fuels to replace conventional diesel consumption. The combustion during DF mode is started when the diesel reaches its auto-ignition temperature. The initiated flash then matures, as in a gasoline engine, and spreads throughout the swept volume in the progress of expansion stroke to ignite the supplied fuel particles. Because of the switching capability of the DF engine, it is regarded amongst the most obtainable and profitable mechanisms for future commercialization [13]. Considering gaseous fuels produced from bio-origin to operate diesel engines in DF mode can be a useful technique to curb the demands of conventional fuels. The good combustion characteristics, low hazardous emissions, and superior knock-resistance make gaseous fuel a great alternative for CI engines. Many engine exports investigated different gaseous fuels like syngas, hydrogen (H_2), PG, natural gas, and biogas to achieve the maximum possible diesel replacement [14]. Among these gaseous fuels, PG could be explored for off-grid power production via DF engines, as it is economically generated from the gasification of biomasses/coal [15]. Waste woodchips and other garden wastes chopped into proper size could be simply used as feedstock for PG synthesis through gasification in rural places [16]. Another concern for the use of PG is that it has poor combustion characteristics as compared to fossil fuel, which affects the engine performance in terms of brake thermal efficiency (BTE) and gives higher carbon monoxide (CO) emissions. Researchers have employed several performance and combustion-improving methods like altering the injection timing (IT), and injection pressure (IP) to boost the performance attributes of DF engines. Using turbochargers in DF engines is another effective solution to the poor combustion attributes of PG. Turbochargers increase the inducted air density thus more oxygen is inducted into the engine which results in better fuel combustion. Another widely accepted and highly effective solution to performance improvement of DF engines using PG is to blend the pilot fuel with a suitable additive. In general, gaseous fuels possess high octane number which instincts to use a high cetane fuel additive to improve the combustion attributes of DF engine. The fuel additive must have high volatility, low viscosity, and better miscibility with pilot fuel to avoid phase separation problem. Blending the fuel additive with pilot fuel was found to be a simple method to alter the desired physiochemical properties of the pilot fuel for DF mode run. While using a separate electronic control unit to inject the desired mass fraction of the fuel additive directly to the combustion chamber makes the DF run more tedious process. This study attempts to improve the combustion and performance attributes of the CI engine operating with PG and curb the engine exhaust emissions by blending DEE with the selected pilot fuels as a cetane enhancer fuel additive.

Section 2 demonstrates a review of recent literature on the use of PG and DEE to emphasize and summarize the findings of various researchers who have studied DF engines using PG. This informative study explores different performance-improving methods employed by researchers working on PG-operated CI engines. In Section 3, the methods implemented during the experiment to acquire the desired experimental observations are elaborated upon. Section 4 presents the attained results in the form of graphs and provides accompanying narratives to explain them. Section 5 outlines the major findings from the experimentation and includes a comparison of these findings with those of other authors in the same area of research. Finally, Section

6 summarizes the findings from the present research work and suggests potential future investigations as part of the scope for further research.

2.Literature review

The objective of the current literature survey is to provide an overview of the aspects to be studied and to emphasize the importance of renewable energy resources in meeting the human race's increasing energy demand. In DF operational mode, special emphasis is given to the use of PG and biogas. Furthermore, the use of cetane enhancer additive in internal combustion engines is summarized from the available literature. The literature conveys the experimental work carried out to use PG in internal combustion engines with adoption of different performance improving techniques by researchers.

Raj et al. [17] studied the synthesis of PG from low-grade coal and madhuca longifolia (Mahua) biomass using a co-gasification process. The researchers also utilized the produced PG in a DF engine to test its performance. The findings showed that the highest diesel saving achieved was 54.2%, at a gasification equivalence ratio (GER) of 0.43, and compression ratio (CR) of 18. The maximum BTE obtained was 27% at GER 0.1, CR 16. During experimentation, CO2 concentration was minimum at 0.8% vol. for operation condition CR 16, 0.43 GER, and 75% mahua blend at maximum engine loading. The minimum unburnt hydrocarbon (HC) was observed for the same 75% mahua blend and at CR 18, 0.43 GER, and full engine loading.

Halewadimath et al. [18] conducted an experimental investigation on DF operation in a CI engine running with H2 mixed PG. H_2 gas was injected at three different positions of the crankshaft 5°, 10°, and 15° after top dead centre (aTDC) and for different durations 30°, 60°, and 90° crank angle (CA). The researchers concluded that the experiments at 10° aTDC and injection duration of 60°CA showed the best performance among all sets of experiments. Emission of NO_x and smoke opacity were found to be reduced by 54.6 and 26.8% respectively.

Nayak et al. [19] performed experiments on a CI engine using a 5% and 10% volume blend of DEE as additives with pilot fuels to enhance the combustion process while using PG. This investigation was intended to assess the combustion, performance, and emission attributes of the CI engine with DEE (5% and 10% by volume) + diesel fuel as pilot fuel with PG as the primary fuel. The study showed that the use of the above-mentioned fuel resulted in lower HC, CO, NOx, and smoke opacity, they concluded that the DF engine running with the DEE+ diesel +PG fuel showed better performance and lower emissions.

Halewadimath et al. [20] researched a DF engine operated with PG. The DF was made to run with different CR, IT, IP, and nozzle geometries. The nozzle geometries were maintained at 3, 4, 5, and 6 holes. Three types of piston bowl geometries were studied for optimum performance and lower emission of the DF engine. The best combination of operating parameters, i.e. CR, IP, IT, and nozzle geometry were found to be 17.5, 240 bar, 27° before top dead centre (bTDC), and 6-hole, 0.1 mm nozzle radius respectively.

Tirkey and Singh [21] performed an investigation on a CI engine by adopting the response surface methodology (RSM) method to identify the best engine operating attributes. The researchers used PG synthesized from Babul woodchip as inducted fuel. The RSM based study was conducted to optimize the input attributes to acquire the finest response in terms of engine performance, blending ratio (BR), IT, brake specific fuel consumption (BSFC), CO emission, and nitric oxide (NO) emission. From the analysis, they concluded that the optimum values of brake power, indicated BTE, BSFC were 3.71 kW, 35.5%, 0.37 kg kWh-1 while the emissions data were recorded to be 0.0091 (vol%), and 245.68 ppm for CO, and NO respectively. All the above results obtained correspond to BR 65%, CR 18.19, and IT 31.11 bTDC.

Singh and Tirkey [22] produced PG from low-grade coal and utilized the generated gas in a DF engine. The researchers used the RSM technique to determine the optimum engine performance. The study intended to maximize BTE and minimize the BSFC and exhaust gases like CO, HC, CO2, and NOx. They reached the maximum diesel saving at CR 16 was 14.38%, at CR 17 it was 22.48% and at CR 17 it was 49.05% in the DF run.

Suryawanshi and Yarasu [23] performed an experiment by varying the shape of carburettors. The study intended to achieve better mixing of PG with intake air. They concluded that 90° angle injection of PG to the intake manifold achieved the highest reduction in engine exhaust.

Halewadimath et al. [24] varied the H_2 content in the inducted PG to improve the performance of DF engines using neem oil biodiesel blends. They noticed that in the presence of H_2 the ignition delay period was reduced with a decrease in combustion duration. The high flame speed of H_2 mitigated the poor combustion trends of PG.

Sabari et al. [25] found brake power of the DF engine increases with load and follows the same trend as diesel alone operation. A similar observation was found by Ambarita [26] in which the power output of the engine operating on DF mode increases with increase in engine speed during the use of biogas as primary fuel.

Kalsi and Subramanian [27] found increased CO_2 emission with an increase in biogas supply due to the presence of large composition of CO_2 which does not participate in the combustion process. It was found higher in DF mode due to the presence of CO_2 in the supplied fuel charge.

Raman and Kumar [28] used DEE as a fuel additive with diesel and blends of mahua biodiesel to examine its impact on performance attributes of the engine. They achieved a 3% increase in BTE with a reduction in BSFC by 12.16% while mixing a 20% volume of DEE with pilot fuels.

Verma et al. [29] studied the influence of changes in gaseous fuel constituents on performance, combustion and emissions of a DF engine. They found that an increase in H_2 percentage in the supplied gaseous fuel mixture enhances the trend of combustion and overcomes the negative combustion attributes, resulting in an increased BTE.

Ahmed et al. [30] conducted experiments to study the performance, emission, and combustion analysis of a CI engine utilising different blends of animal fat oil biodiesel, diesel, and DEE. Animal fat biodiesel was blended with volume fraction of 10 and 20% of DEE. The results revealed that the fuel blend 20% blend of DEE with animal fat biodiesel showed better engine performance with reduction in CO, HC and NOx emissions than that of standard diesel operations.

Gurusamy and Subramanian [31] investigated the effect of DEE blending on a CI engine performance. They revealed that, presence of DEE has shown a decrease in peak combustion pressure, along with a leap in heat release rate. Whereas the BTE increased by 4.5%.

Basha et al. [32] used blends of water-emulsified diesel with DEE volume fractions up to 4% and investigated the performance of a CI engine. They found that the presence of DEE augmented the BTE by 5.3% as compared to the diesel alone run.

Paul et al. [33] performed an experiment with different tertiary blend combinations of diesel-DEE-ethanol. They observed that the engine's BTE augmented with a 5% DEE volume blend and decreased when the volume fraction of DEE was increased to 10%. The use of ethanol and DEE significantly lowers CO, NOx, and HC emissions.

Pushparaj and Ramabalan [34] experimented to use biodiesel produced from cashew nutshell oil and found that it may be used to run diesel gensets without any modifications for small scale power generation fuelled by blend of 20% cashew nutshell oil biodiesel with diesel and 10% DEE volume fraction as an additive.

Hasan et al. [35] studied the influence of DEE and ethanol blends on auto-ignition characteristics of the engine. They varied the intake air temperature in the range of 360 to 420 K with an increment of 15 K at each stage. They conclude that, with presence of DEE the indicated thermal efficiency increased by 11.4%.

Mekonen and Sahoo [36] observed higher BTE and exhaust gas temperature by preheating the biodiesel blends in a DF engine which helped in earlier burning caused by higher cetane number and high oxygen content of biodiesel.

The review of literature on the use of PG indicated a decrease in performance of the engine owing to its inferior combustion attributes. That needs the application of combustion improving techniques for improvement in engine performance. The use of ether group specially DEE as high cetane index fuel additive for CI engines reported in the literature delineated promising outcomes related to engine operation. Simultaneously, the study reveals DEE as a suitable cetane enhancer fuel additive which can be directly injected into the combustion chamber or can be blended with the pilot fuel. However, none of the work reported the utilization of DEE to improve performance of the DF engine running with PG.

The objective of the current experimentation is to evaluate the use of DEE as a high cetane index fuel additive with Karanja oil methyl ester (KOME) blends to boost the performance, combustion and emission attributes of a DF engine while running with PG as the primary fuel. Simultaneously, the impact of DEE on engine exhaust emissions was observed and discussed.

3.Methods

The main aim of this study is to use KOME and PG synthesized through gasification from eucalyptus wood chips. The point for such selection is that KOME and PG are renewable fuels and can be produced economically. This will help in achieving the maximum possible diesel saving in small scale diesel gensets. Whereas the literature points out high CO and HC emissions from DF engines running with PG. The researchers have concluded that using DEE as a fuel additive in DF engines improves its performance and curbs emission levels. This is the reason for selecting DEE as a fuel additive in our research work. The chosen fuels are renewable that will act as a panacea to the energy crisis problem.

3.1Materials and methods

The whole experimental work mechanism has been framed to perform as per the hierarchy presented below in *Figure 1*. During this process, the neat Karanja oil was collected from a local oil mill, which is first treated for degumming with a 1% volume ratio concentration of phosphoric acid. The degummed oil is then processed for biodiesel production by blending properly with a 22% volume of methanol reacted by a 1% volume fraction of sulphuric acid during the esterification of the neat Karanja oil. The mixture is then heated at a constant temperature (65°C) for one hour with steady stirring. Then, in the next phase during the transesterification process, the combination of 22% methanol and 0.5% volume fraction of potassium hydroxide (KOH) was used as a base catalyst. The mixed charge was then whirled for around 2 hours at 60°C at a speed of 80 rpm. After that, the stirring and heating ceased, and the product was left for 1 day in a conical funnel to settle down. The KOME was collected at the top and the glycerine settled down at the bottom of the separating funnel. The KOME accumulated in the funnel was then washed with water properly to remove any traces of methanol from the produced biodiesel. Then the biodiesel synthesized was heated at 65°C for 40 minutes to remove the moisture content. The physical properties of all the combination of pilot fuels were presented in *Table 1*. A downdraft gasifier unit purchased from Ankur Scientific Energy Technology Pvt Ltd., Baroda was used in the current experiment for PG production and eucalyptus wood with 10.2% moisture content was chosen as substrate in the present research. A gas chromatograph-2010 (Chromatography and Instruments Company, Baroda) capable of measuring methane (CH_4), H_2, CO, CO_2 volume fraction in the gas sample was used to check the compositions in the PG sample taken from the outlet of the gasifier. Nitrogen (N_2) gas was used as carrier gas in the gas chromatograph. *Table 2* lists the gas compositions as well as the calorific value (CV) of PG.

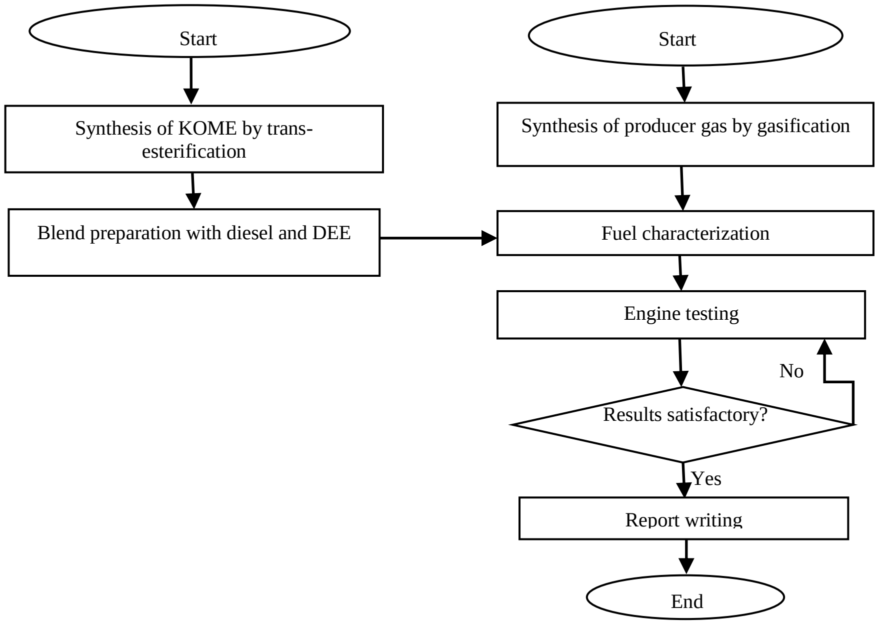


Figure 1 Experimental work mechanism

Table 1 Physical properties of pilot fuels

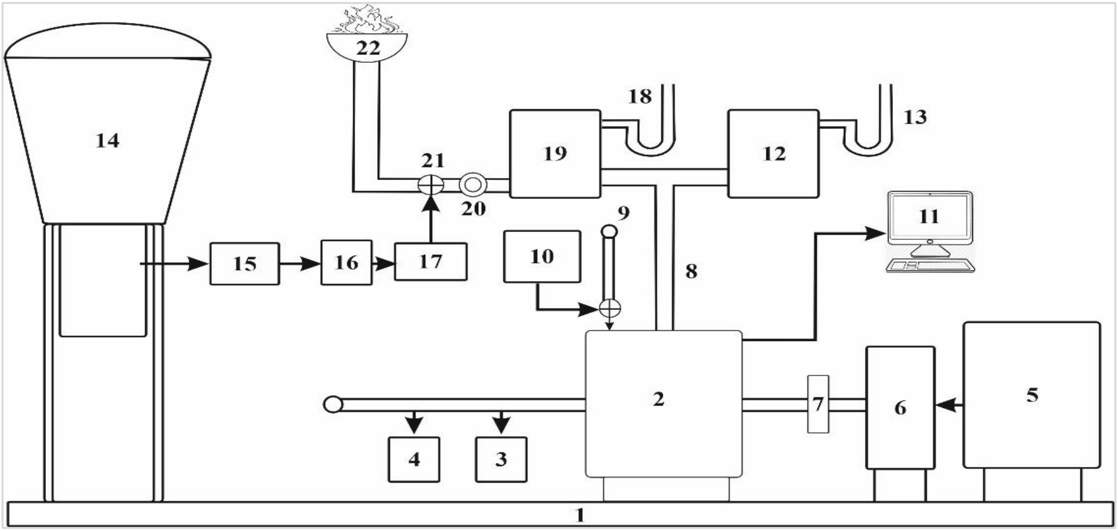
Fuels	Cetane number	Viscosity (cSt, 40 ℃)	CV (MJ kg^{-1})
Diesel	45-55	1.902	42.21
KOME	56.61	4.5	36.12
DEE	125	0.23	33.9
B10	-	2.181	41.5
Diesel+ 5DEE	-	1.82	41.8
B10+ 5DEE	-	2.08	41.12

Table 2 PG compositions and CV

Constituents	CH_4	H_2	CO	CO_2	N_2	CV, MJ Nm^{-3}
PG (%Vol.)	2.72	19.25	20.05	10.47	47.15	5.64

3.2Experimental setup

Figure 2 illustrates the layout drawing of the DF engine, which was chosen for testing. A commercially available Prakash Diesels private Ltd. manufactured CI engine was used for the experiment. The detailed specification of the engine test setup was given in *Table 3*. The engine is transformed into a test setup by attaching retrofits to measure the engine loading, airflow, fuel flow etc. The engine load was applied and varied using a 3-phase, 415-volt, alternator. The cell is constructed with an iron frame that can accommodate halogen lights of various capacities. The loading system is facilitated to load the engine with fractions of full load during experimentation.



1. Bed, 2. Engine, 3. AVL analyzer, 4. Smoke meter, 5. Loading unit, 6. Alternator, 7. Coupling, 8. Intake manifold, 9. Burette, 10. Fuel tank, 11. DAD, 12. Airbox, 13. Manometer, 14. Downdraft-gasifier, 15. Gas cooling system, 16. Passive filter, 17. Fine filter, 18. Manometer, 19. Gas surge tank, 20. Orifice meter, 21. Flow control valve, 22. Burner

Figure 2 Schematic layout of the DF engine

Table 3 Specification of the engine test setup

Make	Prakash diesel Pvt. Ltd.
Rated power	14 Hp (10.44 kW) @ 1500 rpm
No of cylinder	Two
Stroke length	110 mm
Bore diameter	114 mm
Compression ratio	16:1
Injection timing	23˚ bTDC
Injection pressure	220 bar
Alternator	10.3 kW, directly coupled to engine, 21 amp, 3-phase, 415 volt

A gas surge tank is fitted with a manometer, an orifice meter, and a flow regulator valve to adjust and measure the PG supply. The PG synthesized from the gasifier was passed through a water-cooling system to lower its temperature. Then it goes through a passive filter and fine filter to strain any particulate and moisture from the gas. The flammability of the supplied PG was checked at the burner prior to injecting it into the intake manifold. K- type thermocouples were connected at the preferred positions, where each mounting was brazed to the desired elements to give accurate gas temperatures at the engine exhaust, engine cooling water outlet and ambient temperature.

The observed results are collected, recorded, and investigated using a data-acquiring device (DAD). An online AVL-444 model (India) multi-gas analyzer was used to collect the engine exhaust characteristics (CO, HC, and NO), and the AVL-437 model smoke meter was used to measure smoke opacity. In the first phase, experiments were conducted by taking different blends of KOME (10%, 20%, and 30%) on a volume basis with diesel used to operate the engine. In comparison to other blends, the 10% KOME blend with diesel (B10) was observed to be the best with regard to reaching the highest BTE than the other blends. The selected engine was then run in DF operation at maximum engine load with a progressive increase in PG supply in the second phase. Huge engine vibration and loud noise were noticed during the full engine loading operation when the flow rate of PG exceeded 21.49 kg h^{-1}. Hence, to carry out DF mode tests, the 21.49 kg h^{-1} flow rate of PG was considered for further experimentation. In the final stage, a 5% DEE volume fraction (5DEE) was mixed with pilot fuels to improve performance during DF operation, and the same experimentation methods were carried out to compare the results. When the exhaust temperature becomes steady at each engine load, the experimental data were recorded. The observations were recorded three times, and the average values were used for analysis.

The measurement of fuel consumption is determined by the time required for 10 cc of fuel consumption. The mass flow rate of pilot fuel (m_f) can be determined from Equation 1.

$$m_f = \left(\frac{\rho V}{t}\right) 3600 \qquad (1)$$

Where V = Volume of fuel, m^3
ρ = Pilot fuel density, kg m^{-3}
t = Measured time for fuel consumption.

The brake power (BP) was calculated as given in Equation 2. The BTE of the engine was obtained also using Equation 2.

$$\text{BTE}\ (\%) = \frac{\text{BP}}{(\text{mf} \times \text{CVf} + \text{mg} \times \text{CVg}) \times 100} \qquad (2)$$

Where BP = Electrical load applied in kW
CV_f = Calorific value of pilot fuel
m_g = mass flow rate of PG
CV_g = Calorific value of gaseous fuel

4.Results

Experimentation was performed to inspect the role of DEE as a fuel additive on the performance of the CI engine operated using PG and KOME blend concerning change in engine load.

4.1BTE

The efficient consumption of supplied fuel energy is represented in terms of the BTE of the engine. *Figure 3* depicts the change in BTE with variation in engine load. As the engine load is increased, the BTE rises, indicating a faster oxidation rate of the supplied fuel into useful output power. It is obvious that the diesel-only run has shown the best BTE trend of all other test combinations. The poorer CV of PG dictates more supply of fuel to maintain the brake power at respective engine loads. The induction of PG leads to a decrease in oxygen content in the intake air resulting in poor combustion of the fuel charge and the inferior flame speed of PG also leads to a decrease of BTE.

Also, another cause may be the augmented negative compression work in the presence of PG also results in a drop in BTE. While the inclusion of DEE along with the pilot fuels has reflected an improvement in the BTE trend for DF operation with PG. The low self-ignition temperature and comparably high cetane index of DEE suppress the combustion lag caused by the induction of PG. This led to improvement in the combustion process and reflects the influence of DEE in enhancing BTE during the DF run. In comparison to Diesel + PG and B10+PG, blending 5% DEE resulted in better BTE. Highest BTE was recorded to be 27.65% for diesel alone run at an 8 kW engine load. While B10 reached 26.6%, and in the case of DF run Diesel + PG and B10+PG the BTE dropped to 24.2 and 23.75% respectively at the same engine load operation. With the inclusion of DEE, the BTE in the DF run improved and recorded to be 26.7 and 26% for Diesel +DEE+ PG and B10 +DEE+ PG respectively. This enhancement in BTE may be related to the positive effect of DEE on engine combustion such as presence of molecular oxygen in DEE, its comparatively higher flame speed, lower specific viscosity etc. All these attributes of DEE improve the rate of combustion by lowering the ignition delay.

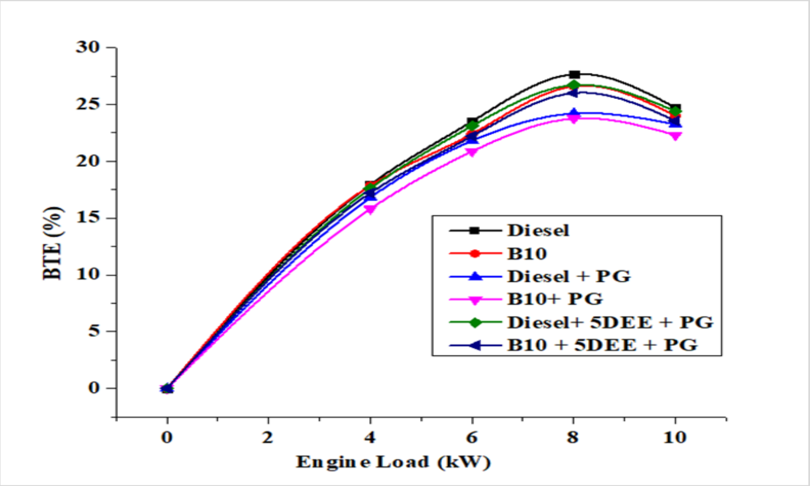


Figure 3 Impact of change in engine load on BTE

4.2Combustion pressure (CP)

Figure 4 shows the variation of CP with respect to CA at full engine load operation. It is observed from the CP curve that a prolonged ignition lag can be marked during DF run as compared to diesel alone operation. This may be linked with the inferior burning qualities of PG like low flame velocity and the presence of CO_2 in the inducted PG being an inert gas that affects the rate of combustion which shifts the peak cylinder gas pressure away from the top dead centre (TDC) during DF run. The apex of CP curve was found to be 6.11 MPa at 9 degrees aTDC for diesel alone run. The apex moved further 6 degrees CA away from TDC for Diesel + PG operation and observed to be 6.45 MPa. Similarly, for B10 + PG, the apex of CP curve was recorded to be 6.4 MPa at 20 degrees aTDC. As the apex of CP moves away from TDC, leading inferior engine performance during DF mode run. The addition of DEE in the form of a blend with the pilot fuels has reduced the ignition delay period as can be detected in *Figure 4*. This signifies the efficiency of DEE in boosting the rate of combustion during the DF run. The apex of the CP curve was recorded to be 6.68 MPa for Diesel + 5DEE + PG and 6.3 MPa for B10 + 5DEE + PG at 15 degrees aTDC respectively.

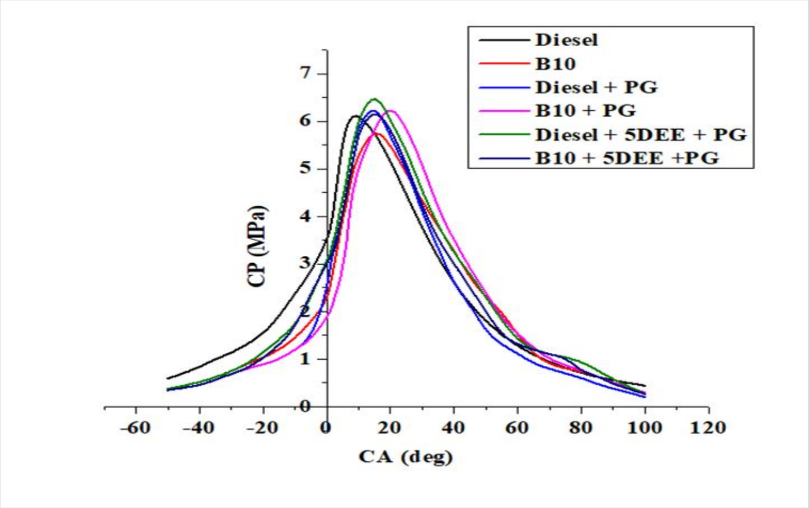


Figure 4 Variation of combustion pressure concerning CA

4.3Hydrocarbon emission

The fraction of fuel energy escaping from the combustion chamber caused by deficient combustion is revealed by the HC emission from the engine exhaust. The variation in the trend of HC emission at different engine loads is presented in *Figure 5*. As compared to a single fuel mode run a very high HC emission was detected during DF operation. The induction of PG with inhaled air during suction stroke reduces both the intake air in the suction volume and lowering the peak temperature. As a result, it slows down the rate of combustion in DF engines, resulting in partial combustion of supplied fuel charge and very high HC emissions as compared to base results. The addition of DEE with pilot fuel accelerates the combustion process, boosting the rate of combustion of supplied PG. This causes a higher rate of conversion of the fuel energy into useful work output and leads to a noticeable drop in HC emission during DF operation. Again, in the presence of the KOME blend used as pilot fuel, a comparatively lower HC emission was observed. This finding could be linked to the molecular oxygen present in KOME that helps in the oxidation of the supplied fuel charge. A similar explanation was also reported by Acharya and Patnaik [37] and Rakopoulos et al. [38]. Diesel + PG showed 64.3% higher HC emission than the base result, while B10 + PG run reached 52.3% higher HC emission, Diesel+5DEE+PG and B10+5DEE+PG have touched 42.8 and 35.4% higher HC emission concerning base result at 8 kW engine loading. This confirms that mixing DEE as a high cetane fuel additive has improved the combustion rate reflected in the reduction of HC emission during DF operation.

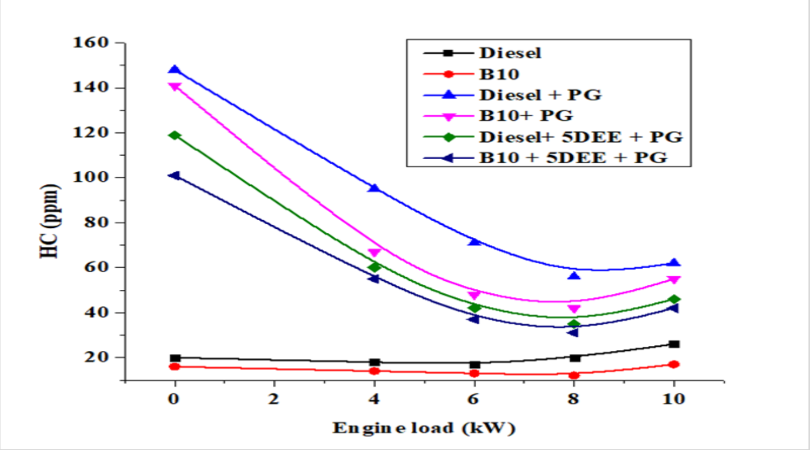


Figure 5 Impact of change in engine load on HC

4.4CO emission

Figure 6 describes the trend of change in CO emission concerning engine load. The lowest CO emission was noticed for the diesel / B10 run than that of all the selected fuel combinations as reflected in *Figure 6*. Diesel + PG has shown the highest CO emission at all engine loads, maybe owing to the poor combustion characteristics of PG and deficiency of intake air due to a reduction in volumetric efficiency with PG induction. Similar explanations were also conveyed by Abdelaal et al. [39]. Again, 20.02% volume of CO content present in the inducted PG is also considered a vital factor in the increase of CO emission during the DF run. The CO emission slightly improved during the DF mode operation with the inclusion of DEE as a high cetane additive. This results in reduced ignition delay owing to the low self-ignition temperature of DEE. It promotes an improved rate of combustion in DF operation and mitigates CO emissions. The oxygen content present in DEE as well as blends of KOME helps in complete oxidation of the supplied fuel charge, which leads to lowering CO emissions. At full load operation, again a rise in CO emissions was noticed during the DF mode run. This can be referred to as the increase in rich mixture pockets in the combustion zone with increased pilot fuel supply. This results in partial combustion of the fuel charge and hikes the rate of CO formation.

At full load run, the CO emission recorded for B10 + 5DEE + PG is 0.3% in the engine exhaust, which increased to 0.36% for Diesel + 5DEE + PG, 0.49% for B10 + PG and 0.66% for Diesel + PG as linked to base result 0.04%. This signifies that the blending of DEE with diesel or B10 has shown a positive influence on the combustion of inducted PG improving the oxidation rate of CO into CO_2.

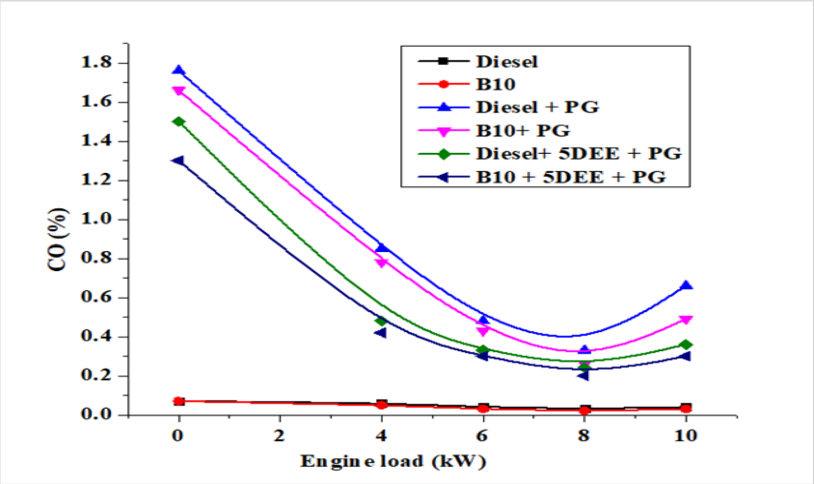


Figure 6 Impact of change in engine load on CO emission

4.5NO emission

Figure 7 depicts the variation in NO emission concerning engine load. NO emission is primarily caused due to the oxidation of inhaled nitrogen in the intake air at a temperature above 900˚C [40]. The NO emission from the engine mainly depends upon three factors; the temperature within the combustion chamber reaching above the range suitable for thermal NO formation, accessibility of oxygen in the combustion zone, and the time interval for which the temperature remains in the zone for thermal NO formation. As observed from the graph, the NO emission rises with a hike in engine load. The cause behind this may be referred to as the increase in combustion temperature and pressure with increased pilot fuel supply that increased the ignition centres leading to superior combustion within the engine cylinder.

A high NO emission was noticed during diesel or B10 alone operation. While with the induction of PG, the NO emission falls drastically throughout all engine loads. The credit for this drop in NO emission can be linked to a drop in the fresh air intake during suction due to PG induction leads to an increase in the delay period, resulting in a decrease in combustion duration for NO formation. The drop in combustion temperature owing to poor combustion attributes of PG as explained earlier also results in a drop in thermal NO formation. The presence of DEE as a fuel additive has shown a slight rise in NO emission, reflecting the improvement in combustion during the DF run with the addition of DEE. Diesel + PG showed 50.4% lower NO emission than the base result, while the B10 + PG run reached 64% lower NO emission, B10 + 5DEE + PG and Diesel + 5DEE + PG gave 54 and 50.9% lower NO emission concerning diesel run at 100% engine loading.

4.6Smoke opacity

The change in the trend of smoke opacity under the influence of PG induction at various engine loads was illustrated in *Figure 8*. The presence of aromatic compounds in the supplied fuel mainly gives rise to smoke formation. It is found that with the rise in engine load, the smoke opacity gradually increases. This can be linked to an increase in pilot fuel injection with an increase in engine load that leads to a higher diesel supply in the combustion zone increasing the availability of aromatic compounds during combustion.

While during the DF operation, the PG induction results in lowering the diesel supply and hence lowers the aromatic compounds in the combustion chamber leading to a comparable drop in smoke opacity. A similar explanation was also given by Nayak et al. [41] during their experiment in DF operation. The use of the B10 blend along with DEE addition further reduces the existence of aromatic compounds in the combustion chamber, subsequently giving the lowest smoke opacity value throughout the engine loads. Diesel+PG showed 29.7% lower smoke opacity than the base result, while the B10+PG run reached 44.5% lower smoke opacity, Diesel+5DEE+PG and B10+5DEE+PG have exhibited 33.7 and 51.3% lower smoke opacity respectively concerning to base result at full engine load run.

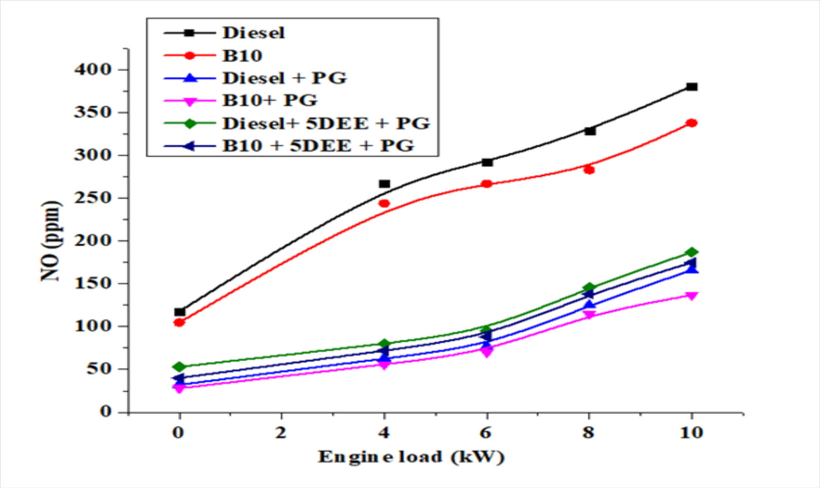


Figure 7 Impact of change in engine load on NO

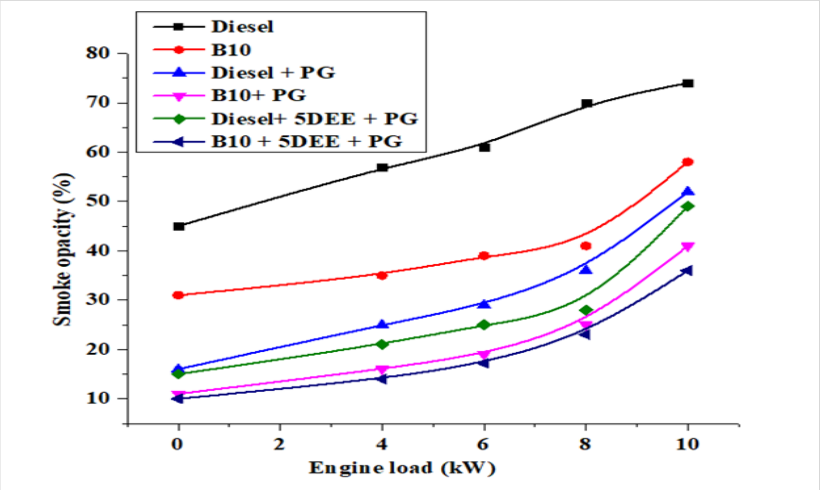


Figure 8 Impact of change in engine load on smoke opacity

5.Discussion

In this investigation, DF mode operation with PG demonstrated a drop in BTE owing to poor combustion attributes of PG. Hence, a suitable combustion enhancer fuel additive with high cetane index is needed to increase the DF engine performance. Out of many combustion improvers we have selected DEE as a fuel additive as it is easily available and completely miscible with diesel. Key findings from this experimentation are the inclusion of DEE as a fuel additive has shown an increased BTE for engine operation with PG that comes closer to base results. As a combustion enhancer many attributes of DEE, like lower boiling point, low self-ignition temperature, and comparably higher flammability range helps in combustion during DF run. As DEE possess lower viscosity and density that helps in better atomization and spray formation pattern of the injected fuel. These factors helped in lowering the ignition lag caused due to induction of PG owing to the wider flammability range of DEE. As a whole DEE helps in improving the engine performance. Other major factors are the presence of oxygen molecules in DEE and KOME which helped in better combustion of supplied fuel charge. The presence of DEE also lowered the engine emissions like CO, HC, and smoke opacity during the DF run as observed in the present experiment. The NO emission from DF engines was found to be lower than engine operation in single-fuel mode.

Further improvement in BTE and engine emissions can be achieved to minimize the variation observed from standard diesel operation. Apart from using fuel additives other strategies like the use of turbochargers and preheating the intake air can be considered for performance improvement of DF engines. Advancing fuel IT is another technique by which the effect of ignition lag can be reduced. Better atomization of sprayed fuel will lead to better vaporization which in turn will lead to better combustion. Finally, simulation-based combustion analysis can be conducted to have a better understanding of the combustion of fuels inside the DF engine. Statistical tools can be used to design the experiment to use higher blends of DEE or trail further combination of ternary blend of diesel + DEE + KOME. The use of DEE as fuel additive in blend form is easier to achieve. The response surface method may be considered to validate the observed experimental results as well as to frame the design of the experiment for future progress in this research work.

A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

The primary objective of this experiment was to investigate the impact of DEE on the performance and exhaust attributes of a DF engine using PG as the primary fuel. Blending DEE with diesel in the DF run resulted in a similar trend of performance parameters compared to running the engine solely on diesel. The addition of DEE as a fuel additive improved the rate of combustion, leading to an increased BTE during DF mode operation. However, the apex of the CP curve shifted slightly away from the TDC when PG was supplied during the DF run due to an increase in ignition lag. On the other hand, including DEE with pilot fuels as a high cetane index additive reduced ignition lag during the DF run and advanced the combustion attributes of the DF engine. Notably, the use of PG during DF operation led to a significant reduction in NO emissions and smoke opacity. Furthermore, the presence of DEE as a fuel additive in the DF run resulted in reduced smoke opacity, as well as decreased HC and CO emissions compared to running the DF engine without DEE. As a result, employing PG as a gaseous source of energy can be a viable option for operating DF engine-based gensets to electrify off-grid rural areas. Additionally, utilizing B10 blends of KOME with DEE as a high cetane additive can partially reduce diesel consumption.

Further improvements in performance attributes can be achieved by optimizing the combustion process through modifications to the IP and IT parameters of the DF engine.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Sanjaya Kumar Mishra: Investigation, experimental data collection, conceptualization, writing original draft and editing. **Pradipta Kumar Dash:** Investigation and result analysis. **Shakti Prakash Jena**: Supervision, conceptualization, reviewing, and editing.

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Appendix I

S. No.	Abbreviation	Description
1	ρ	Pilot Fuel Density
2	5DEE	5% Volume of Diethyl Ether
3	aTDC	After Top Dead Centre
4	bTDC	Before Top Dead Centre
5	B10	10% Karanja Methyl Ester Blended With Diesel on a Volume Basis
6	BP	Brake Power
7	BR	Blending Ratio
8	BSFC	Brake Specific Fuel Consumption
9	BTE	Brake Thermal Efficiency
10	CA	Crank Angle
11	CH_4	Methane
12	CI	Compression Ignition
13	CO	Carbon Monoxide
14	CO_2	Carbon Dioxide
15	CP	Combustion Pressure
16	CR	Compression Ratio
17	CV	Calorific Value
18	CV_f	Calorific Value of Pilot Fuel
19	CV_g	Calorific Value of PG
20	DAD	Data-Acquiring Device
21	DEE	Diethyl Ether
22	DF	Dual Fuel
23	GER	Gasification Equivalence Ratio
24	H_2	Hydrogen
25	HC	Hydrocarbon
26	IP	Injection Pressure
27	IT	Injection Timing
28	KOH	Potassium Hydroxide
29	KOME	Karanja Oil Methyl Ester
30	m_f	Mass Flow Rate of Pilot Fuel
31	m_g	Mass Flow Rate of PG
32	N_2	Nitrogen
33	NO	Nitric Oxide
34	NO_x	Oxides of Nitrogen
35	PG	Producer Gas
36	RSM	Response Surface Methodology
37	t	Measured Time for 10 cc Fuel Consumption
38	TDC	Top Dead Centre
39	V	Volume of Fuel in m^3