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Thermodynamic study in a diesel engine using karanja biodiesel-diethyl ether-producer gas

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Abstract

In the current experimentation, a thermodynamic assessment was performed in a 4-stroke compression ignition engine (CIE) running in dual-fuel mode. The ternary blend of karanja biodiesel, diethyl ether along with diesel was used as pilot fuel and producer gas was used as inducted fuel to run the engine. The findings indicate that brake-specific energy consumption (BSEC) increased with the induction of producer gas (PG). The mixing of diethyl ether (DEE) by 5% on a volume basis has reduced the BSEC in dual fuel run that approaches the base result (diesel alone operation). The exergy destruction and exergy efficiency curve also indicate the positive influence of DEE on dual fuel performance. 10% volume blend of karanja oil methyl ester with diesel (B10) when further mixed with a 5% volume blend of DEE gave the highest diesel saving of 86.7% in dual-fuel run with PG followed by B10 + PG (84.5%), Diesel + 5DEE + PG (83.6%) and diesel + PG (78.5%) at 80% engine load operation.

Keywords

Biodiesel, Diethyl ether, Producer gas, Exergy destruction.

1.Introduction

The need for energy is rising due to a variety of factors, including an increase in the number of commercial vehicles in the transportation sector that are mostly compression ignition engines (CIE) [1]. The use of CIE in the agriculture sector, construction sector, and so on, all of which are reliant on fossil fuel-based energy source [2]. Fossil fuels were mostly expected to go on for a limited year, viewing upon the present rate of use. As a result, scientists began focusing on renewable resources such as biomass-based biofuel and especially non-edible oil [3]. The CIE is also a significant shareholder to global warming as it releases emissions such as particulate matters, carbon dioxide (CO_2), nitrogen oxides (NO_x), and other harmful gases [4]. Exponential hike in exploitation of fossil-based energy sources directly linked with two important problems: energy crisis and increase in environmental pollution. The use of renewable gaseous fuel in dual-fuel (DF) engines can be a penetrative way to reduce the dependency on fossil fuels.

Different researchers experimented with hydrogen, compressed natural gas, producer gas, biogas as a source of renewable gaseous fuel [5]. Producer gas (PG) can be considered as a suitable combustible gaseous fuel, synthesized by flowing steady air stream through the bed of coal or hot coke. Woodchip from different garden waste can be easily used as substrate for PG production in rural areas. PG can partially replace diesel consumption in DF engines to run small-scale generators for electricity. PG operates more efficiently with diesel engines in DF run because of the high compression ratio operating condition [6]. It also plays a crucial role in reducing NOx emissions, smoke, and particulate matter at a cost of increase in brake specific energy consumption (BSEC). The main challenge with use of PG as alternative fuel is it gives lower efficiency as compared to diesel or natural gas or petrol engines [7]. Hence, researchers worked with different combustion improving techniques like using air pre-heater, turbocharger, altering the engine operating attributes such as injection timing, injection pressure (IP), and compression ratio (CR), use of combustion improving fuel additives, application of thermal barrier coatings on engine components, etc. to

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enhance the performance of PG operated engines. Out of all these techniques, fuel modification (use of fuel additives) seems to be simple, easier, and cost effective. This research work aims to improve the performance of the CIE running with PG under the influence of a suitable cetane enhancer fuel additive.

Section 2 illustrates a literature review to highlight the critical aspects of DF operations with PG as primary fuel. The literature also presents various fuel modification techniques attempted to improve performance of DF engines along with other combustion improving techniques used by different authors for PG operated engines. Section 3 represents the methodology followed by the authors to obtain required experimental data. Section 4 illustrates the obtained findings in form of graphical representations. Section 5 elaborates the key findings and the limitations of the present study, and Section 6 concludes the attempted researcher work and highlights the future scope for further exploration.

2.Literature review

Researchers have used PG as inducted fuel in DF engines with various alternative pilot fuels.

Nayak and Mishra [8] experimented with a DF engine to accomplish higher brake thermal efficiency (BTE) and lower engine exhausts. During experiment they varied the injection parameters and shapes of the combustion chamber. They found that biodiesel-PG revealed proficient results for overall engine performance, emissions. It showed lower BTE and minimal exhaust emission of hydrocarbon (HC), NO_x, and smoke opacity.

Carlucci et al. [9] conducted an experiment on upgrading the performance in a CIE operated by PG as inducted fuel and blends of biodiesel as pilot fuel by varying its IP. They noticed an improvement in combustion characteristics with a decrease in carbon monoxide (CO) and HC emissions.

Lal and Mohapatra [10] experimented to observe the influence of CR on combustion characteristics of a CIE using PG as inducted fuel. They found a reduction in ignition delay with the rise in CR and accomplished lower fuel requirement per unit power output at CR 18.

Bates and Dolle [11] experimented on a DF diesel engine using PG derived from woodchips. They concluded that approximately 3/4th of the diesel fuel required to operate a genset using PG in DF mode.

Akkoli et al. [12] experimented the influence of variation in injector nozzle diameter, number of nozzle holes on the performance of the CIE running in DF mode. They concluded that, 0.25 mm nozzle diameter and 6 number of nozzle holes gave 5.8% enhancement in BTE.

Suryawanshi and Yarasu [13] studied the effect of different angles of Y-shape carburetors on PG-air mixing. They found that, 90° angle of mixing gave the best reduction in engine emissions with PG induction.

Yaliwal and Banapurmath [6] experimented using biodiesel-PG in DF mode with and without hydrogen enrichment. They found that hydrogen enrichment has improved the net heat release and combustion pressure with a reduced exhaust emissions during biodiesel-PG operation.

Many researchers selected fuel modification approaches over other accessible methods since it is simple, straightforward to examine the performance of a CIE. The addition of a suitable combustion improver as an additive in fuel with different proportions of blend was experimented by various engine exports. Researchers have used diethyl ether (DEE) as a combustion enhancer while testing the use of other alternative fuels in CIE.

Basha et al. [14] prepared blended fuels of water emulsified diesel with DEE up to 4% and experimented in a CIE. They revealed that DEE blending with water emulsion increased the BTE by 5.3% compared to the base reading.

Yesilyurt and Aydin [1] observed that with an increase in DEE fraction in the blend showed a decrease in peak cylinder pressure and heat release rate. While exhaust emissions such as CO, NO_x, and smoke were decreased compared with standard diesel run.

Raman and Kumar [15] experimented with different combinations of diesel-mahua biodiesel blends with DEE. They found that 20% blend of mahua biodiesel with diesel mixed with 20% DEE on a volume basis gave the best results in terms of performance by enhancing BTE by 3% with a reduction of brake specific fuel consumption (BSFC) by 12.16% as compared to standard diesel.

Loganathan et al. [3] found that DEE blending with cashew nutshell biodiesel along with hydrogen induction showed higher combustion pressure, rate of heat release and increased NO_x emission than base results. Further, most of the researchers focused on study of engines performance like BTE, fuel economy, diesel saving, and emissions. They ignored the thermal losses from the engines while running with alternative fuels. Exergy analysis measures how far the actual system deviates from ideal performance. Internal irreversibility in the engine is responsible for the discrepancy between expected and observed engine efficiency. To analyze the irreversibility associated with processes, 2nd law of thermodynamics needs to be applied. The destruction of exergy is due to the poor conversion of fuel energy into productive mechanical energy under different loading conditions of a CIE. The trimming of irreversibility can improve engine performance by following the 2nd law of thermodynamics [16].

Exergy losses from a CIE can be decreased by raising the in-cylinder temperature, which improves the combustion and reduces irreversibility during combustion resulting higher exergy efficiency [17].

Jena and Acharya [18] experimented to reduce the exergy destruction of a dual fuel engine by applying thermal barrier coating to increase the mean temperature of combustion.

Verma et al. [19] performed an exergy-emission analysis of a DF engine running with hydrogen enriched biogas. They found that in the presence of hydrogen, the exergy efficiency of the DF engine increased from 23.3 to 25.5% owing to better flammability of hydrogen with a decrease in CO and HC emissions.

Sarkar and Saha [20] noticed significant improvement in energy and exergy efficiency due to pre-heating of intake air in DF mode.

Rangasamy et al. [21] experimented with a reactivity-controlled diesel engine in DF mode. They noticed improvement in BTE with reduction in exergy destruction as compared to standard diesel run.

Selmane et al. [22] experimented with a turbocharged DF engine with hydrogen. They noticed improvement in BTE and exergy efficiency with increase in air-fuel equivalence ratio. Researchers attempted various methods to improve performance of DF engines. Simultaneously, verified the influence of these methods on DF engine performance by exergy study of the engine. Application of cetane enhancer in form of ternary fuel in DF engine running with PG remained untouched. Limited works were reported on exergy analysis of a PG operated DF engine.

The goal of this research work is to use thermodynamic analysis to examine the changes in engine irreversibility patterns while running with alternative renewable fuels. This will instinct to achieve higher diesel saving with lower exergy destruction. Hence, a detailed energy and exergy study was attempted using standard diesel, and its blend with karanja oil methyl ester (KOME) under the influence of DEE as additive to improve performance in a DF engine with PG as inducted fuel.

3.Methods

The study will focus on use of biodiesel from neat karanja oil and PG generated from woody biomass. The fact for such choice is that these two renewable fuels are commonly available and can be produced in an inexpensive way. Again, DEE as fuel additive shown positive influence on performance of DF engines. Hence, DEE was selected as the cetane enhancer fuel additive in the present work. All the alternative selected fuels are renewable in nature and can achieve remarkable diesel saving with proper optimization of engine parameters. Simultaneously, attention must be kept on variation in trends of exergy efficiency and exergy destruction (ED) with the substitution of alternative fuels in the selected CIE.

3.1Thermodynamic analysis

The importance of energy and exergy study leads to identifying the rate of energy losses and accordingly working on effective utilization of resources to boost the performance of a CIE. The supplied fuel energy is partially transformed into useable mechanical energy, and the rest portion of the energy was lost as heat loss to cooling medium, heat energy taken away via exhaust gas, chemical energy loss through unburned emissions, and energy destroyed unaccountably. The energy utilization efficiency may be increased through optimization of energy distribution.

The assumptions considered for current energy and exergy analysis are:

- The engine operates at a steady state.
- The whole engine is considered as control volume.
- Ideal gas equations are valid for air at inlet and gases at the exhaust manifold.
- The change in potential energy and kinetic energy was neglected.

The energy imparted (Q_{in}) to the CIE is stated as Equation 1.

$$Q_{in} = m_f \times CV_f + m_g \times CV_g \qquad (1)$$

Here, m_f specifies the rate of pilot fuel supply, CV_f calorific value of pilot fuel, m_g is the substitution rate of PG, CV_g calorific value of PG.

In consequence of the 1st law of thermodynamics, the energy balance of the system is expressed as Equation 2.

$$Q_{in} = W_e + Q_{out} \qquad (2)$$

Where the rate of work output (W_e), and the rate of energy lost (Q_{out}) was expressed in kW.

The consumption of exergy (E_x) may be stated as Equation 3 based on 2nd law of thermodynamics.

$$E_x = Q_{in}\left(1 - \frac{T_L}{T_H}\right) = W_e + \delta E_x \qquad (3)$$

Where E_x = rate of exergy supply to the system in kW
δE_x = exergy destruction rate in kW.
T_H = Peak temperature of the cycle
T_L = Ambient temperature
BTE measures the rate of transformation of fuel energy into useful work
The BTE was calculated using Equation 4.

$$BTE = \frac{W_e}{Q_{in}} \qquad (4)$$

Similarly, the exergy efficiency (η_{ex}) was calculated using Equation 5, defined as the ratio of rate of useful work extracted from the system to the rate of exergy supplied to the system.

$$\eta_{ex} = \frac{W_e}{E_x} \qquad (5)$$

3.2Materials and methods

Figure 1 illustrates the complete experimental working mechanism of the attempted research work. The neat karanja oil was first obtained from the crusher mill and was treated with phosphoric acid at a concentration of 1% volume ratio during this process. The karanja oil is degummed before processing for biodiesel synthesis using the transesterification method. The esterification of crude oil was performed, in which degummed karanja oil was appropriately blended with 22% volume of methanol and 1% volume ratio of sulphuric acid.

Then it is heated for one hour at 65°C in a constant temperature bath with continuous stirring. Then in transesterification, methanol of volume ratio 22% and potassium hydroxide (KOH) base catalyst (0.5 percent volume ratio) were used to make a reagent combination. The combined charge was then stirred with heating continuously at a speed of 80 rpm for about 2 hours at 60°C. Then the mixture was left to settle for around 24 hours. The collected KOME was water washed and heated at 70°C for 30 minutes to evaporate unreacted methanol and moisture present in it.

3.3Experimental test rig and procedure

Figure 2 shows the schematic diagram of the DF engine chosen for experimentation. A downdraft gasifier was used to deliver PG. The woodchip of eucalyptus with moisture percentage 10.2% was chosen and chopped into the desired size is being used as feedstock in the gasifier. The constituents in the PG sample were tested through a gas chromatograph (model GC2010 Chromatography and Instrument Co, India). The gas constituents and calorific value (CV) of PG are presented in *Table 1*. Presence of 20% CO, 19.22% hydrogen (H_2), 2.75% CH_4 defines the combustible character of the PG sample collected from the gasifier.

Table 1 Constituents and CV of PG

Gas compositions	**PG (Volume %)**
CO	20.03
CO_2	10. 5
H_2	19.22
CH_4	2.75
N_2	46.49
CV, MJ Nm^{-3}	5.64

The specifications of the selected engine are 14hp, 4-stroke, twin cylinder, CIE with a rated speed of 1500 rpm and 16.5:1compression ratio. A 3-phase, 415volt AC alternator was used to apply and vary the engine load. A water manometer, orifice meter, and flow control valve are attached to the gas surge tank to regulate and measure the substitution rate of PG. A PG injector was fitted into the inlet pipeline to inject the PG with the intake air.

A data acquiring system (DAS) is provided to collect, record, and investigate the observed results. Before allowing the PG to gas surge tank, its flammability test was performed at the burner till a bluish flame appears due to combustion of PG. Software package “Engine Soft LV” of version 9 was used for online performance analysis. In the initial phase, studies were carried out using different volume fractions (10%, 20% and 30%) of KOME with diesel to run the CIE. The 10% volume blend of KOME with diesel (B10) was found to be the most effective in terms of obtaining maximum BTE compared to other blends.

Then in the second phase, the CIE was operated in DF mode at rated power output with a gradual hike in PG substitution. When PG flow rate increased beyond 21.49 kg h^{-1}, huge engine vibration with high noise was observed. Hence the PG flow rate was fixed at 21. 49 kg h^{-1} to record the further dual fuel observations. In the final stage, to enhance the performance during DF operation, 5% volume of diethyl ether (5DEE) was blended with diesel and B10 respectively on a volume basis, and the same experimentation steps were performed to compare the findings. The physical properties of all the selected pilot fuels are represented in *Table 2*. Cetane number of DEE was quite higher than diesel and KOME. This will have a positive influence on performance of DF engine. Similarly, viscosity of DEE was also quite lower than KOME and diesel. This will help in better atomization and spray formation of ternary blend as compared to B10. Which, play a vital role CIE combustion.

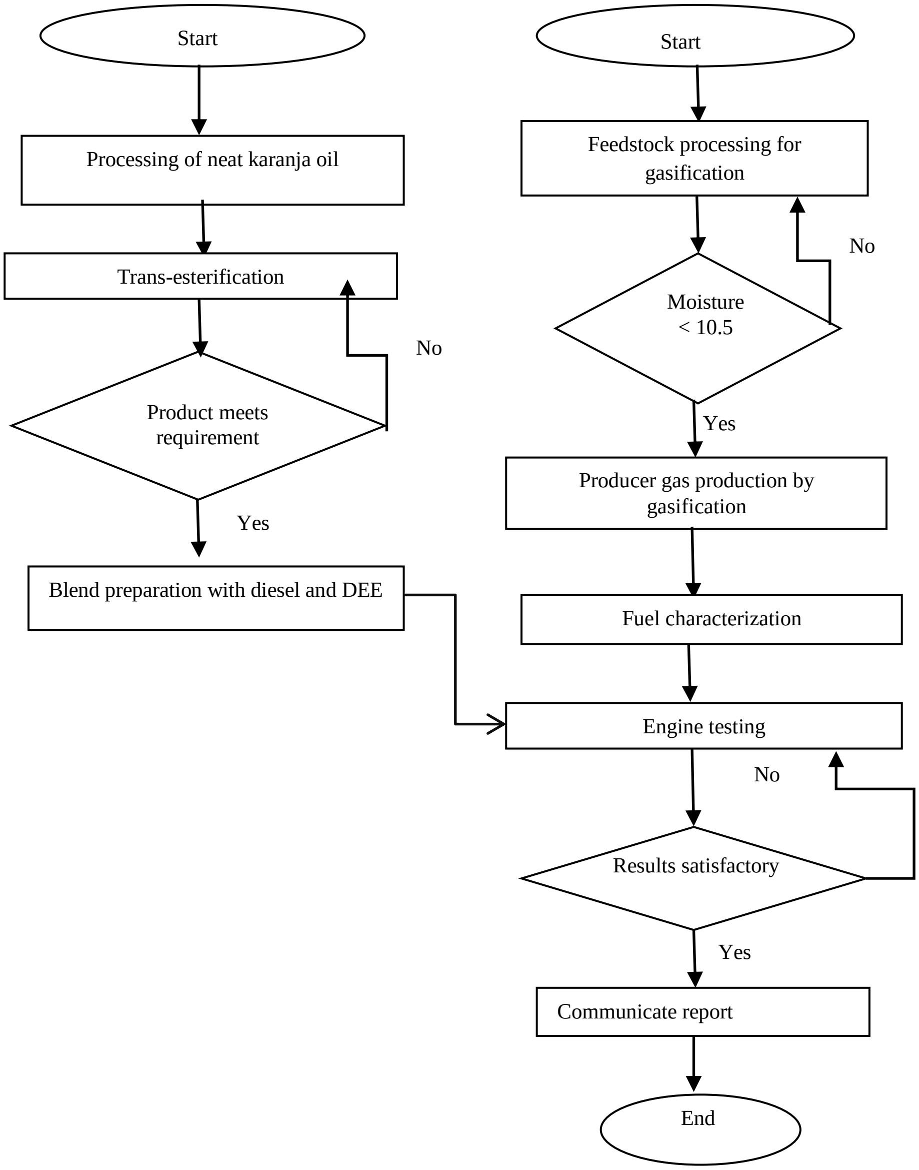
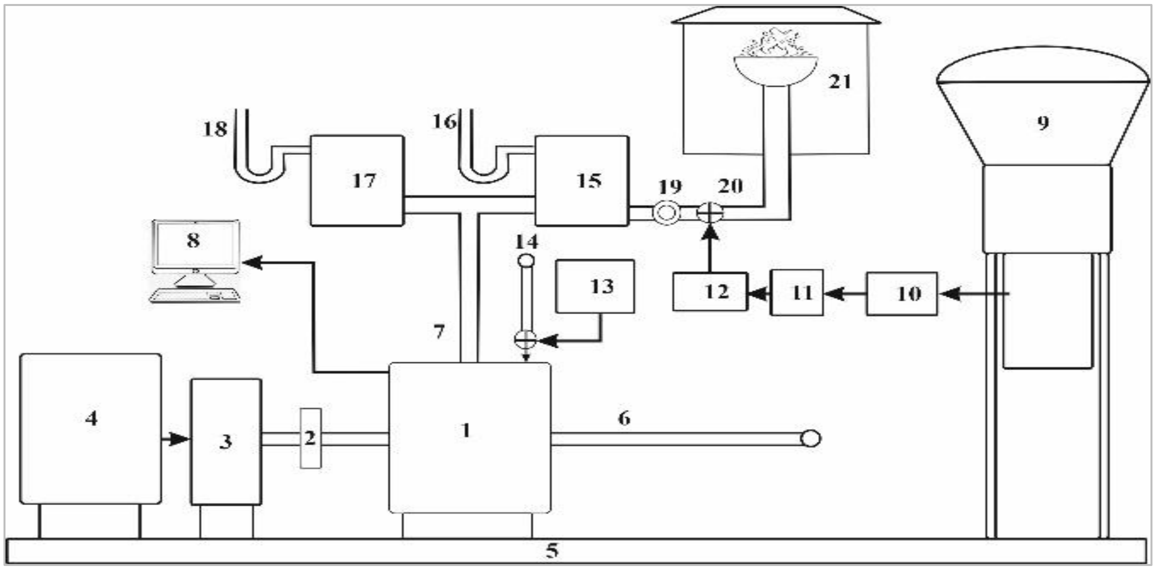


Figure 1 Experimental working mechanism



1. Engine, 2. Coupling, 3. Alternator, 4. Loading unit, 5. Bed, 6. Exhaust pipe, 7. Inlet pipe, 8. DAS, 9. Gasifier, 10. Cooling unit, 11. Passive filter, 12. Fine filter, 13. Fuel tank, 14. Burette, 15. Gas surge tank, 16. Manometer, 17. Airbox, 18. Manometer, 19. Orifice meter, 20. Flow control valve, 21. Burner

Figure 2 Schematic diagram of the DF test rig

Table 2 Physical properties of pilot fuels

Fuels	**Viscosity (cSt, 40^0 C)**	**Cetane number**	**CV (MJ kg^{-1})**
Diesel	1.902	45-55	42.21
KOME	4.5	56.61	36.12
B10	2.181	-	41.5
DEE	0.23	125	33.9
Diesel+ 5DEE	1.82	-	41.8
B10+ 5DEE	2.08	-	41.12

4.Results

The experimental data were recorded in each load when the exhaust temperature reached a steady-state. The observations are recorded thrice, and their average values are considered for final computation.

4.1Brake specific energy consumption

The BSEC represents the effective utilization of supplied fuel energy per unit power output [15]. *Figure 3* illustrates the change in BSEC trend with variation in brake mean effective pressure (BMEP). The observations indicate a decreasing trend of BSEC with an increase in BMEP for all the tested fuel combinations. May be owing to the increase of in-cylinder temperature and pressure at higher engine load, resulting in enhanced heat release rate. The induction of PG in dual fuel operation has shown higher BSEC. The reason behind this could be the lower CV of PG; its combustion characteristics, like low flame speed, low cetane index, and presence of CO_2 also inhibits the combustion process. To mitigate these effects of PG combustion, when 5% DEE was blended with both the selected pilot fuels, the BSEC reduced at all BMEPs in DF operations. This improvement can be linked with the positive influence of DEE on combustion, such as its comparatively high flammability, higher flame speed, presence of molecular oxygen, etc. Again, the volatile nature and lower specific viscosity of DEE also improves the atomization, vaporization, and spray formation during its combustion led to lowering the ignition delay. Diesel + DEE + PG have shown nearly closest BSEC curve as diesel alone curve than all other fuel combinations. B10 + DEE + PG also showed better BSEC than Diesel + PG and B10 + PG. At full load operation, Diesel + PG and B10 + PG required 17.67 and 18.43 kJ kWh^{-1} BSEC, respectively, to give the same power output as that of standard diesel operation (14.6 kJ kWh^{-1}). Whereas B10 + 5DEE + PG and Diesel + 5DEE + PG have shown 16.2 and 14.7 kJ kWh^{-1} BSEC, respectively, that reflects the progress in the performance of DF engine with DEE blending.

4.2Brake thermal efficiency

Figure 4 represents the BTE of the DF engine concerning to change in BMEP. The BTE of an engine represents the effective conversion of heat energy into useful brake power. BTE increases with the rise in BMEP, showing the enhanced rate of conversion of fuel energy into useful brake power.

Diesel alone operation have shown the highest BTE, followed by Diesel + DEE + PG, B10, B10 + DEE + PG, Diesel + PG, and the lowest BTE was observed for B10 + PG. It was obvious that standard diesel operation has gave the highest BTE than all the combinations of PG operation. The lower CV of PG requires a higher fuel supply rate to compensate for the same rate of power output. Blending of 5% DEE with both the pilot fuels, respectively have shown improved BTE as compared to Diesel + PG and B10 + PG. This reflects the influence of DEE owing to its high flammability that suppresses the ignition delay caused by PG induction. The presence of molecular oxygen in DEE also help in improving the combustion process in DF mode led to increase the BTE.

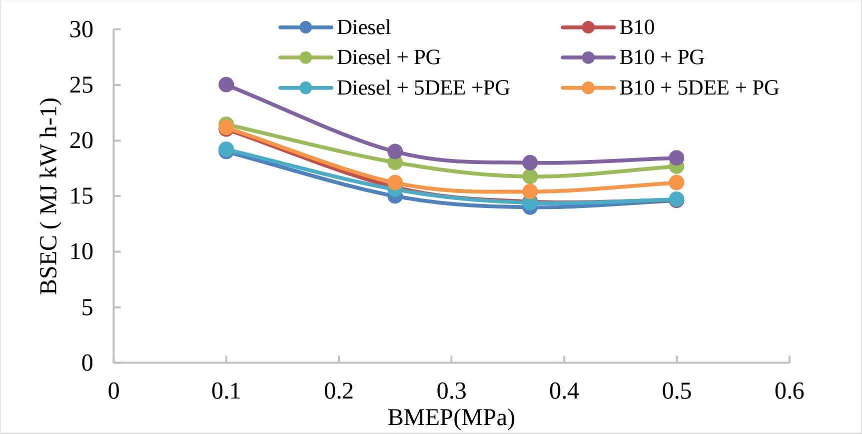


Figure 3 Variation in BSEC concerning to BMEP

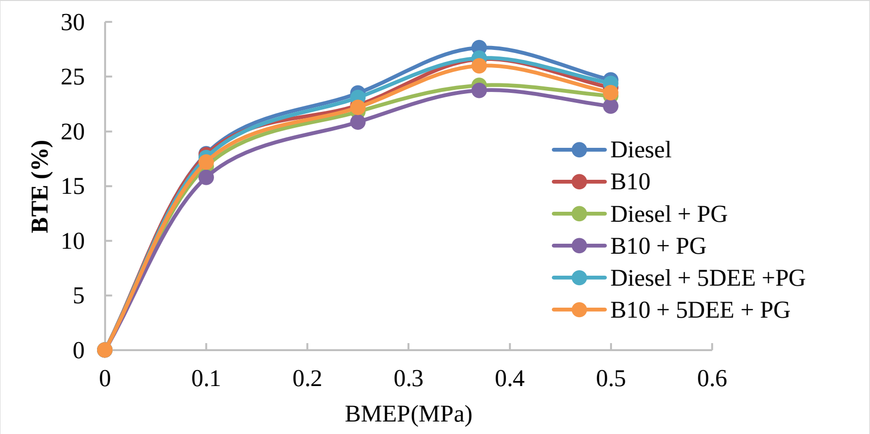


Figure 4 Variation in BTE concerning to BMEP

Diesel + DEE + PG have shown higher BTE than B10 alone run. Diesel + PG and B10 + PG have shown 5.91 and 9.71% drop in BTE, respectively, as compared to the base result. In contrast Diesel + DEE + PG (1.21%) and B10 + DEE + PG (4.65%) shown a slightly lower drop in BTE, that confirming the positive influence of DEE.

4.3Exhaust gas temperature

To optimize the performance of a CIE while running with alternative fuels, exhaust gas temperature (EGT) could be a vital attribute to study the variation in engine performance. *Figure 5* illustrates the change in EGT concerning to the increase in BMEP. The EGT varies between 158 to 345^0 range for all the selected fuel combinations at full load operation. Dual fuel run has showed higher EGT than standard diesel or B10 alone operation. A similar trend of the results was also reported by Nayak et al. [23]. The slow combustion trend of PG leads to delayed heat release and comparatively more fuel burns in the after burning stage.

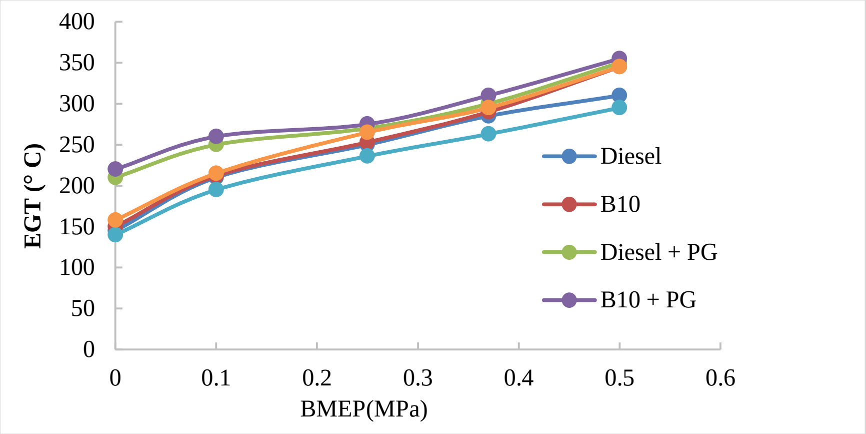


Figure 5 Variation in EGT concerning to BMEP

This leads to comparatively elevated EGT during DF operation. The blending of DEE with pilot fuels has shown a drastic drop in EGT for DF operation. The high cetane index of DEE mitigates the effect of ignition delay caused by PG induction, ensuring better conversion of released heat energy into brake power. The influence of DEE may have minimized the combustion of supplied charge in after burning stage. As a result, drastic drop in EGT was noticed at lower BMEPs.

4.4Exergy efficiency

The variation in the trend of exergy efficiency concerning to BMEP is presented in *Figure 6*. The ratio of actual power output from the highest achievable power output from the system is defined as exergy efficiency. Diesel alone run shown the highest exergy efficiency. The lower CV of PG affects the maximum possible work extracted from the engine. Again, the presence of PG with the intake air also lowers the volumetric efficiency by reducing the volume of fresh intake air. This dilution effect also affects the combustion and led in drop of mean temperature of combustion that reduces the peak temperature too. As a result, the exergy efficiency decreases in dual fuel run. The presence of DEE improves the combustion rate, promoting combustion of supplied PG in the continuous combustion phase. This results in increased conversion to useful work output from the supplied fuel energy. Diesel alone run showed 33.1% exergy efficiency, while Diesel + PG reached 30.37% and B10 + PG run achieved 29.04% exergy efficiency. B10 + 5DEE + PG and Diesel + 5DEE + PG have showed 30.46 and 31.8% exergy efficiency respectively.

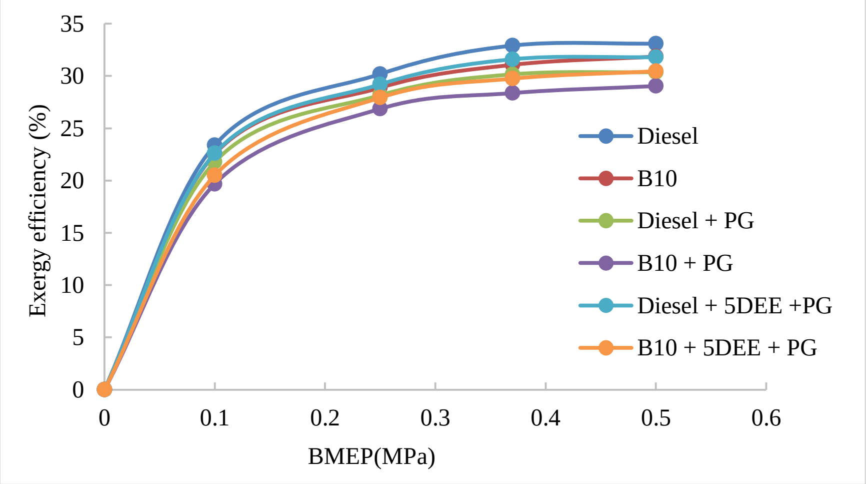


Figure 6 Variation in exergy efficiency concerning to BMEP

4.5Exergy destruction

The quantity of unused exergy lost from the system (engine) in terms of exergy lost to the cooling system, exergy lost through engine exhaust, through friction loss, and unaccounted losses, all sums up to define total ED from the engine. *Figure 7* depicts the variation in ED concerning to BMEP. Diesel alone operation gave the lowest ED as compared to all the tested fuel combinations. At all BMEPs, B10 + PG had shown the highest ED, could be due to the poor combustion properties of PG, which became much worse when B10 was used as a pilot fuel instead of diesel. When DEE was employed as a combustion enhancer in a DF operation, the ED decreased. DEE raises the cetane index of both pilot fuels and shortens the ignition lag phase. This results in efficient combustion of supplied fuel charge and mitigates ED in dual fuel operation. At full load run, B10 + PG showed 4.13% increase in ED and B10 + 5DEE + PG, Diesel + 5DEE + PG, Diesel + PG have showed 1.7, 0.5 and 3% increase respectively in ED as compared to base result.

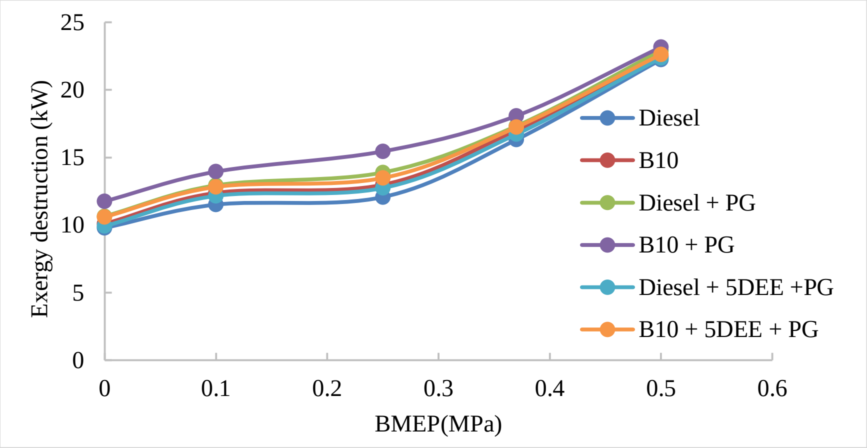


Figure 7 Variation in exergy destruction concerning to BMEP

4.6Diesel saving

The variation in diesel saving trend concerning to BMEP was illustrated in *Figure 8*. Highest diesel saving achieved at BMEP 0.4 MPa for B10 + 5DEE + PG (86.7%) followed by B10 + PG (84.5%), Diesel + 5DEE + PG (83.6%) and Diesel + PG (78.5%). The blending of KOME in the presence of DEE insists improved combustion of the inducted PG. The molecular oxygen present in KOME and DEE also minimizes the deficiency of intake oxygen caused by induction of PG. The inclusion of DEE as a blend in pilot fuels provides effective utilization of energy share given by PG combustion. Hence, combination B10 + 5DEE + PG helped to achieve the highest diesel saving in the said operating condition.

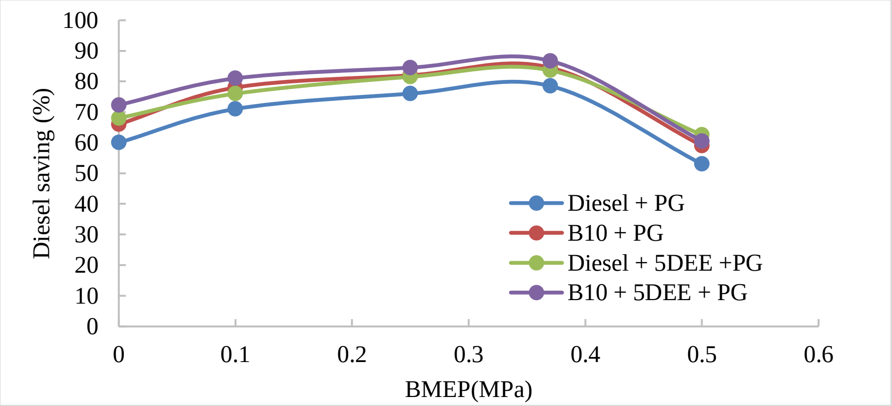


Figure 8 Variation in diesel saving concerning to BMEP

5.Discussion

In the current experimentation, DF mode run with PG shown a decrease in BTE, exergy efficiency along with a higher BSEC for the same unit power output. Hence, DEE was selected as a cetane enhancer to improve the poor performance of PG operated DF engine. The key findings observed from this experimental works are: addition of DEE with pilot fuels had shown an improved energy and exergy conversion in DF engine. Simultaneously, decrease in EGT in presence of DEE reveals a decrease in exergy loss through engine exhaust. The improvement in engine performance can be attributed to the lower boiling point, viscosity, density, and lower autoignition temperature of DEE compared to diesel, and blends of KOME. The molecular oxygen present in KOME and DEE also minimizes the deficiency of intake oxygen caused by induction of PG. The high cetane index of DEE mitigates the effect of ignition delay caused by PG induction, ensuring better conversion of released heat energy into useful work. This results in improved engine performance while using PG. Also, the high flammability range of DEE influences the combustion during DF run at all BMEPs. This results in a better conversion of intake fuel energy into brake power output, improving the BTE and exergy efficiency during DF operation. As a result, in the presence of DEE, larger diesel savings (86.7%) were achieved with a comparable reduction in exergy destruction when compared to DF runs without DEE as a fuel additive. Beside this, still a huge amount of exergy was destroyed at higher BMEPs of engine operation. Addition of cetane enhancer fuel additives must be accompanied with other proven combustion improving techniques like pre-heating the intake air, use of appropriate capacity of turbochargers. Both these techniques will reuse heat energy lost through the exhaust of the engine, that could result in reduction of ED from the DF engine. Advancing the injection timing can be attempted to supress the effect of ignition delay. This will allow the injected fuel for better spray formation and vaporization resulting better combustion. Simulation based combustion analysis of the DF engine running with PG may highlight the scopes to improve the overall performance of the engine. Application of thermal barrier coating on combustion chamber can be considered to improve the combustion as well as performance of the DF engine.

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

6.Conclusions and future work

From the above research work, the following findings were strained:

- Diesel + 5DEE + PG have shown comparable performance attributes as that of base results (diesel-run).
- The presence of DEE in the form of a combustion enhancer drastically reduced the BSEC and ED in DF mode run with PG.
- The EGT also reduced from DF run with PG in the presence of DEE, which leads to reducing the energy losses through engine exhaust.
- B10 + 5DEE + PG gave the highest diesel saving of 86.7% at BMEP 0.4 MPa.

Hence, being a non-edible oil-based biodiesel KOME blend up to 10% volume in addition to 5% blend of DEE as a combustion enhancer in ternary blend can be considered to power DF generators with PG induction for electricity production in rural areas.

The exergy efficiency and ED trend with ternary pilot fuel can be enhanced by increasing the equivalence ratio while running with PG. Similarly, application of thermal barrier coating in components of combustion chamber will be another approach to improve performance of the DF engine. Further, improvement can be achieved by optimizing injection pressure, injection timing to improve the combustion of CIE. Still the energy lost through exhaust could be reused to preheat the intake air or employing a turbocharger to increase the density of fresh air supply to the DF engine to ensure better combustion and performance.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Authors contribution statement

Pradipta Kumar Dash: Data collection, investigation, data curation, and draft manuscript preparation. **Shakti Prakash Jena:** Conceptualization, writing – original draft, analysis and interpretation of results. **Harish Chandra Das:** Study conception, supervision, investigation on challenges.

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Appendix I

S. No.	Abbreviation	Description
1	5DEE	5% Volume of Diethyl Ether
2	B10	10% Volume Blend of Karanja Biodiesel
3	BMEP	Brake Mean Effective Pressure
5	BSEC	Brake Specific Energy Consumption
6	BSFC	Brake Specific Fuel Consumption
7	BTE	Brake Thermal Efficiency
8	CH_4	Methane
9	CIE	Compression Ignition Engine
10	CO	Carbon Monoxide
11	CO_2	Carbon Dioxide
12	CR	Compression Ratio
13	CV	Calorific Value
14	CV_f	Calorific Value of Pilot Fuel
15	CV_g	Calorific Value of Producer Gas
16	DAS	Data Acquiring System
17	DEE	Diethyl Ether
18	DF	Dual Fuel
19	ED	Exergy Destruction
20	EGT	Exhaust Gas Temperature
21	Ex	Rate of Exergy Consumption
22	H_2	Hydrogen
23	HC	Hydrocarbon
24	IP	Injection Pressure
25	KOH	Potassium Hydroxide
26	KOME	Karanja Oil Methyl Ester
27	mf	Rate of Pilot Fuel Supply
28	mg	Rate of Producer Gas Supply
29	NO_x	Oxides of Nitrogen
30	PG	Producer Gas
31	Q_{in}	Energy Supplied to the Engine
32	Q_{out}	Rate of Energy Loss
33	T_H	Peak Temperature in the Cycle
34	T_L	Ambient Temperature
35	W_e	Rate of Work Output
36	δE_x	Rate of Exergy Destruction
37	η_{ex}	Exergy Efficiency