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Effect of additives on the stability of ethanol-diesel blends for IC engine application

Ramkumar Shanmugam[1] · Parthasarathy Murugesan[1] · Gedisa Gudeta Guye[1] · Boopathi Duraisamy[2]

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Abstract

The present research work was conducted on a compression ignition engine to assess the engine characteristics fueled with the blend of diesel and high-oxygenated additives such as ethanol. Ethanol does not easily blend with diesel. In order to attain a homogeneous mixture, a small amount of additive is added to the blend. Different additives were added to the blend to form a homogeneous mixture. Stability test was conducted on the blend to ensure prolonged homogeneity. The additives used for the test purpose were isopropanol, oleic acid, and ethylene acetate. From the stability results, it was found that oleic acid was the best additive which produces a better homogenous mixture for the blend of ethanol and diesel. One percentage of oleic acid is used as an additive to blend ethanol and diesel. The different combinations of blend ratios used for the test purpose were D90E10, D80E20, and D70E30. All the aforementioned blends have low cetane number because of ethanol, which was compensated by adding 1% DEE (diethyl ether) to all the blends. Experimental results exhibit that there is an improvement in the performance characteristics, such as brake thermal efficiency (BTE) and specific energy consumption (SEC), with the enrichment of DEE in ethanol-diesel blend. It is also noticed that the blend without DEE exhibited lower magnitude. This is mainly due to higher energy content and cetane number of DEE. Emission characteristics, like hydrocarbon (HC) and carbon monoxide (CO), were found to drastically increase with the increase in the ethanol concentration in the diesel blend. This is attributed to higher latent heat of vaporization (LHV) of ethanol present in the blend. Combustion pressure and heat release rate of the DEE-enriched ethanol blends were higher by 2.2 % and 2.4 %, respectively, when compared with their corresponding blends without DEE. This is a result of higher volatility of DEE which leads to better combustion.

Keywords Oxygenate additives · Diesel · Ethanol · Fuel blend stability · NO_x reduction

Abbreviation

aTDC	After top dead center
BP	Brake power
BSEC	Brake specific energy consumption
bTDC	Before top dead center
BTE	Brake thermal efficiency
CN	Cetane number
CO	Carbon monoxide
CO_2	Carbon dioxide
CV	Calorific value of fuel
DEE	Diethyl ether
ID	Ignition delay
J	Joule
kg	Kilogram
kJ	Kilojoule
kW	Kilowatt
LHV	Latent heat of vaporization
mJ	Megajoule
NO_x	Oxides of nitrogen
SOC	Start of combustion
UBHC	Unburnt hydrocarbon

Ramkumar Shanmugam and Parthasarathy Murugesan contributed equally to this work.

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✉ Ramkumar Shanmugam
yesram98@gmail.com

✉ Parthasarathy Murugesan
msarathymech@gmail.com

1 Department of Automobile Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India

2 Department of Automobile Engineering, SRM Institute of Science and Technology, Kattankulathur, India

IC	Internal combustion
D90E10	90% diesel and 10% ethanol in volume
D80E20	80% diesel and 20% ethanol in volume
70E30	70% diesel and 30% ethanol in volue
HRR	Heat release rate
EGT	Exhaust gas temperature

Introduction

The oil reserve has been continuously depleted and this leads to increase in pollution and increase in the cost of the fossil fuel. A tremendous increase in vehicle population leads to demand for petroleum fuels. The usage of petroleum fuel increases the global warming, which leads to serious problems such as climate change and rises in the sea level (Bragadeshwaran et al. 2018). Exhaustion of petroleum fuels and enlargement of environment pollutions are the main problems to search other sources for the diesel engines. Reports of various researchers, published in the last 3 years on fossil fuels, show fast falls in its reserves which strongly suggests for various alternatives. A diesel engine is widely used as a power source in the agricultural sector, passenger vehicles, and mobile and immobile generators (Panahi et al. 2019). With an increase in the population, the usage of engine increases and the demand for fossil fuel also increases. The emission due to the burning of fossil fuel also increases; greenhouse gas also increases. The usage of biofuel produces a nullified effect on carbon dioxide because of the lesser cycle period. This leads to the search for alternate fuels which reduces the usage of fossil fuel (Ramalingam et al. 2020). Today, the world has been using petroleum products like petrol and diesel to meet the energy demands in transportation, agriculture, and industrial sector. All the economic activities are in a way related to energy in the present-day society (Janakiraman et al. 2020). The use of energy from fossil fuel leads to an environmental hazard. At the same time, the demand for energy is also growing at an alarming rate. The world is turning towards renewable sources such as vegetable oil, biogas, and alcohol. These fuels are easily available, biodegradable, non-toxic, and eco-friendly (De Menezes et al. 2006). Compression ignition engines are widely used as a power source for transportation vehicles and to generate electricity; it's because of its higher efficiency than SI engine and durability. However, they are considered a major source of air pollution in urban areas due to their black smoke, oxides of nitrogen, hydrocarbon, carbon monoxides, carbon dioxide emissions, and particulate matter (Torres-Jimenez et al. 2011). Alcohol fuels are alternative for petroleum-based fuels. Alcohol is made from renewable resources like biomass such as sugarcane, sugar beet, and wood and from waste products like waste paper, grass, and tree. It can be used as fuel for both compression ignition engine and spark ignition engine. Ethanol has advantages in agricultural feedstocks, because it is highly biodegradable, renewable, and a promoter of rural economy (Guo et al. 2011; Hariz and Takriff 2017). Direct usage of pure ethanol cannot be implemented in CI engine. Blends of ethanol and diesel can be used as fuel. Many researchers have done their research on ethanol-diesel blend but none of the researchers has done their research in the usage of additive to increase homogeneity and the cetane number. Some of the reviews on the usage of alcohol, diesel, and biodiesel are done and summarized below.

Yesilyurt and Aydin (2020) had done a research on blends of cottonseed oil biodiesel, diethyl ether, and diesel. The different fuel and its blend ratios used for the test purpose were D100, B20, D77.5B20DEE2.5, D75B20DEE5, D72.5B20DEE7.5, and D70B20DEE10. The peak BTE is achieved at the load of 1000 W; further increase in the load decreases BTE. Because of higher viscosity of biodiesel, the combustion quality gets reduced, which leads to reduction in BTE. With the increase in the percentage of diethyl ether in the blend, BTE increases. Diesel produces the highest unburnt hydrocarbon (UBHC) when compared with other test fuels, followed by B20. With the increase in the percentage of diethyl ether (DEE) in the blend, UBHC emission decreases. This is because of the increase in the percentage of oxygen content with the addition of DEE. The authors capped the percentage of DEE to 10% of the volume in the blend; this is because the further addition of DEE stops the engine to operate at higher loads. With the increase in the concentration of DEE, CO_2 emission decreases, which may be due to the increase (decrease) in oxygen (carbon) content in the blend. Addition of diethyl ether in the blend reduces the CO emission; this is because of higher cetane rating of DEE which increases combustion temperature. Gnanamoorthi and Devaradjane (2015) have analyzed ethanol concentration varied from 0 to 40% in the blends of diesel. One percentage of ethyl acetate and diethyl carbonate was used to make the blend stable. The engine was tested with various compression ratios ranging from 17.5 to 19.5. A higher compression ratio leads to improved combustion quality. At a higher compression ratio, say 19.5:1, the blend of ethanol 40% and diesel 60% produces a higher BTE than diesel. This is because high compression provides higher compression temperature before the combustion process, which increases the ease towards igniting the fuels that have a high auto-ignition temperature. With the increase in compression ratio, HC and CO emissions decrease; the presence of inbuilt oxygen is yet another factor for the reduction of HC and CO emission. Górski and Przedlacki (2014) have analyzed the physical and thermal properties of DEE blended with diesel. Miscibility test and cetane number analysis were also done on the blend. With the increase in the percentage of DEE in the blend, the calorific value, viscosity, and density decrease. The cetane number of the DEE is higher than that of diesel, which leads to an increase in the cetane rating of blends, thus resulting in a lesser ignition delay. The blend of DEE and diesel showed better performance characteristics than that of diesel. These blends also proved to have good combustion characteristics when the engine had a higher cylinder pressure and heat release rate (HRR). Liu et al.

(2019) have done an experiment on a CI engine fueled with blends of polyoxymethylene dimethyl ethers, ethanol, and diesel. Polyoxymethylene dimethyl ethers have inbuilt oxygen content and high cetane number which act as a cetane improver in the ethanol-diesel blend. Ethanol-diesel blend containing polyoxymethylene dimethyl ether showed outstanding performance. This blend also exposed lesser HC and CO emission when compared with diesel.

Qi et al. (2011) tested stability of the blend of biodiesel 70 %, diethyl ether 5%, diesel 15%, and ethanol 10%. With the addition of ethanol and diethyl ether to biodiesel, smoke and CO emission reduced, but HC emission increased. The additives diethyl ether and ethanol do not have appreciable influence over the cylinder peak pressure. Ibrahim (2018) has assessed the impact of oxygenated additive with biodiesel on CI engine. With the addition of five percentage DEE, the BTE is higher when compared with biodiesel and diesel blend. High LHV and low calorific value of DEE reduce the combustion quality that results in the reduction of the BTE. Higher oxygen content in biodiesel and DEE leads to higher HRR than diesel. The author tested the characteristics of the engine running on different blends of soybean biodiesel–diesel–water containing acetone–butanol–ethanol (ABE). Water containing ABE solution showed a BTE of 7.88% higher than that of neat biodiesel blend. At peak load condition, diesel, BD50, and BD75 produced almost an equal amount of BTE. During high load conditions, the lubrication property of biodiesel led to producing more BTE, while during low load conditions, its high viscosity had created poor atomization and large droplets, thus leading to lower efficiency. The lower cetane number aided the fuel to remain in the combustion chamber for the slightly extended duration. In addition, the low viscosity also helped in creating better atomization, besides the better combustion due to oxygen content. ABE-biodiesel-diesel blends emitted very less amount of NO_x than diesel. The blend which has water containing ABE emits less NO_x than the blends without it. The amount of NO_x emitted is inversely proportional to the percentage of water containing ABE in the blend, although water containing ABE has similar properties to that of biodiesel (rich oxygen and low cetane number). This resulted in a lesser amount of NO_x than biodiesel. This is due to ethanol's higher latent heat of vaporization and low heating value, which reduced the cylinder temperature. The lower cetane number of waters containing ABE had led to a higher ignition delay and also increased the duration of peak temperature. Water containing ABE emits less particulate matter since it is having rich oxygen content. It emits just 69.3% of particulate matter emitted by diesel (Chang et al. 2014).

The design of experiment chosen by researcher is in a such way that it has both direct and indirect injection facility, i.e., it has injectors placed on both head and throttle body. The engine was being operated at three test conditions: in all three operating conditions, B30D70 was directly injected in to cylinder. The first operated condition did not have any additive at throttle body injection; the second operating condition had ethanol at throttle body injection; and the third operating condition had the blend of di-*tert*-butyl-peroxide-ethanol at throttle body injection. The engine running on biodiesel blend with ethanol injection showed a higher inlet and exhaust temperature than while running without ethanol injection. This is because the ethanol injected along the manifold had reduced the inlet and exhaust temperature. Mere B30D70 emitted more NO_x. B30D70 with ethanol injection emitted less NO_x than without ethanol injection, since ethanol is having a high LHV (840 kJ/kg) than diesel (200 kJ/kg) and soybean biodiesel (270 kJ/kg). This is due to the reduction in the peak temperature. When the 15% energy share, ethanol with B30D70 emitted 190 ppm of NO_x, while without ethanol injection, the same fuel emitted 481 ppm of NO_x (Ferreira et al. 2013). Di-*tert*-butyl peroxide is having a high cetane–improving property. Due to this, the cylinder temperature and pressure are increased. The fuel with additive emitted more NOx but less CO. The emission of HC is directly proportional to the percentage of ethanol injected into the inlet manifold. The engine, while running on 70% diesel–30% soybean biodiesel without the injection of ethanol, emitted 11 ppm of HC, whereas the same engine with the same fuel with 15% ethanol injection emitted 75 ppm of HC. Traces of the ethanol injected in the manifold get trapped within the cervices and escape from combustion; due to this, emission of UBHC increases, another reason for the emission of more UBHC being the absence of oxidation (Shaafi and Velraj 2015). The author has tested various blend ratios of diesel–biodiesel–butanol and keeping diesel as a reference fuel. For all the fuels used, there was a decrease in BSFC wherever there was an increase in the load. The SFC produced by diesel is lower than that produced by used cooking oil biodiesel and used cooking oil biodiesel–butanol blend. This is because diesel is having a higher calorific value than biodiesel and butanol. When there was an increase in the load, the exhaust gas temperature (EGT) increased, irrespective of the fuel used. The EGT of diesel was found to be higher than that of biodiesel, biodiesel–butanol blend, and biodiesel–diesel blend. HC emission was found to be lesser when the engine was running on vegetable oil. Butanol was found to have a higher latent heat of vaporization than cooked vegetable oil biodiesel and diesel. Due to this phenomenon, combustion was incomplete and the emission of HC was higher. Increasing the load decreased the emission of CO, irrespective of the fuel used. When the engine was running on 46% of load, it emitted more CO because there was an increase in the concentration of butanol. When there is an increase in the ratio of butanol in the blend, emission of NOx decreased, since it is having a high LHV (Yilmaz et al. 2015). The main inspiration of focusing on DEE-enriched ethanol-diesel blend was to substantially minimize NOx emission without compromise performance characteristics. The removal of high temperature zone in the chamber owe it to the reduction of NOx emission. The primary reason for formation of smoke emission is high secondary combustion phase in the cycle. Moreover, this lower combustion temperature results in a rise in CO and HC due to post-combustion oxidation regions. In addition, fresh charger impingement on cylinder wall is also a reason for the rise in the HC emission. Based on that, the aim of the present study is (1) to investigate the conventional CI engine to be operated with DEE-enriched ethanol-diesel blend as a fuel; and (2) to study the stability of blends to ensure prolonged homogeneity with different additives such as isopropanol, oleic acid, and ethylene acetate.

Materials and methods

Selection of fuels and blends stability

Ethanol is a renewable and sustainable source of energy for SI engine. It could not use a sole fuel in the CI engine. This is mainly due to lower density and high self-ignition temperature leading to incomplete combustion and knocking in CI engine. Various methods have followed ethanol used as fuel in CI engine. A small fraction of ethanol blend with diesel can be used as a fuel in an unmodified CI engine. This blend may exhibit slightly lower performance than diesel fuel but drastically reduce the NO_x emission. Ethanol and diesel do not blend and form a homogeneous mixture at normal temperature. To make the blend homogenous, different additives were used and then the stability was analysed. The additives used for the test purpose were isopropanol, oleic acid, and ethylene acetate. It was found that the oleic acid was the best additive which produces a better homogenous mixture of ethanol and diesel. One percentage of oleic acid is used as an additive to blend ethanol and diesel. The different blends of ethanol and diesel used were 10% ethanol–90% diesel (D90E10), 20% ethanol and 80% diesel (D80E20), and 30% ethanol-70% diesel (D70E30). Figure 1 shows the different ratios of ethanol-diesel blend without additive and with different additives. It was noticed that the blend of ethanol-diesel is more homogenous with oleic acid. In all the blends of ethanol and diesel, one percentage of oleic acid is added. Table 1 shows the stability of ethanol-diesel blend with different additives. The stability of ethanol and diesel has been analyzed for 90 days. The additives used to analyze the test blends were isopropanol, oleic acid, and ethylene acetate. The different ratios of ethanol and diesel blend used for the test purpose were (i) 10% ethanol–90% diesel (DE10%), (ii) 20% ethanol and 80% diesel (DE20%), and (iii) 30% ethanol-70% diesel (DE30%). One percentage oleic acid and one percentage diethyl ether were blended with of ethanol-diesel blend for all blend ratios. The mixtures' stability was analysed visually and was tabulated as shown in Table 1. Table 2 shows the physical and thermal properties of diesel, diethyl ether (DEE), isopropanol, ethanol, and oleic acid. After the analyses of different ratios, we selected the combination of the blends with the best additives to investigate the performance analysis of diesel engine by using 1% oleic acid as a surfactant.

Table 2 shows the physical and thermal properties of diesel, diethyl ether (DEE), isopropanol, ethanol, and oleic acid. After different ratios of analysis are done, we selected the combination of the blends with the best additives to investigate the performance analysis of diesel engine by using 1% oleic acid as a surfactant. Form the fuel properties, it was found that ethanol has a very lesser cetane number when compared with diesel. This reduces the overall cetane number of the blend. Thus, from the literature review, it was found that diethyl ether has a cetane number of 125, so one percentage of it has been added to all the ethanol-diesel blends.

Experimental setup and procedure

The engine used for the test purpose was a single-cylinder, naturally aspirated, water-cooled, compression ignition engine. The injection pressure used was 220 bar. The detailed specification of the engine used for the test purpose is shown in Table 3. The engine used was operated at a constant speed of 1500 rpm, and the load was varied from 0 to 100%. Figure 2 shows the schematic diagram of the experimental setup. Figure 3 shows the valve timing of the engine. Before conducting the experiment, the engine was overhauled and a new lubricating oil was used. The loading device and emission analyzer were serviced and calibrated before the experiment. The engine tests were carried out at a constant speed of 1500 rpm at different load conditions of 25%, 50%, 75%, and 100%. The fuel flow rate was adjusted according to the load conditions by the governor. After every fuel test, the fuel tank was cleaned, and the engine was operated with diesel for 15 min to clean the fuel system. For each set of load condition, the engine was allowed to stabilize, and 100 ml of fuel was used to take one set of reading. Three sets of reading were taken for one test condition.

The engine speed was controlled by the governor. Water was supplied through the engine block and cylinder head sockets to cool the engine. The piezoelectric pressure transducer was fitted in the cylinder head to measure the in-cylinder pressure. Eddy current dynamometer was coupled with the engine to give load on the engine. At the beginning, the engine was run without load to attain steady-state conditions. The next stage of experimental work was carried out with various inlet air temperatures ranging from 80 °C to 100° C without EGR. AVL Digas analyzer was used to measure engine exhaust emissions like UBHC, NO_x, CO2, CO, and excess oxygen in the exhaust. Non-dispersive infra-red (NDIR) technique was used to measure the gases like CO, CO2, and UBHC. The technical specifications of the AVL Digas analyzer are given in Table 4.

Uncertainty analysis

The present investigation contains the use of different instruments to measure the physical parameters. The precision of types of equipment can be influenced by many environmental factors. The accuracy of measurement should be considered for all uncertainty and error analysis. Uncertainty analysis could be done by each physical parameter and zero calibration. It also considered the fixed and random error of measurement. The precision of the measured variable and calculated variable is mentioned in Table 5 (Parthasarathy et al. 2020).

Uncertainty of measured physical parameter is given by Δx_i

$$= \frac{2\sigma_i}{x_i} \times 100 \quad (1)$$

Let E be the calculated quantity $E = (x1, x2, x3, .., xn)$ (2)

The calculated value of uncertainty of experimental work was:

$$\Delta E = \sqrt{\left\lfloor \frac{\partial E}{\partial x_1} \Delta x_1 \right\rfloor^2 + + \left\lfloor \frac{\partial E}{\partial x_2} \Delta x_2 \right\rfloor^2 + \left\lfloor \frac{\partial E}{\partial x_3} \Delta x_3 \right\rfloor^2 + \ldots + \left\lfloor \frac{\partial E}{\partial x_n} \Delta x_n \right\rfloor^2}$$

$$= \sqrt{[N]^2 + [T]^2 + [g]^2 + [\mathrm{UBHC}]^2 + [CO]^2 + [\mathrm{Smoke}]^2 + [\mathrm{CP}]^2 + [\mathrm{NOx}]^2 + [\mathrm{BSEC}]^2 + [\mathrm{BTE}]^2}$$

$$= \sqrt{[1]^2 + [0.5]^2 + [0.1]^2 + [1.0]^2 + [0.7]^2 + [1.1]^2 + [0.3]^2 + [1.4]^2 + [0.5]^2 + [0.7]^2}$$

$$= 2.6\%$$

Table 1 Stability of ethanol-diesel blend with different additive

Fuel	10 Days	20 Days	30 Days	40 Days	50 Days	60 Days	70 Days	80 Days	90 Days
D90E10 + 1% Oleic Acid	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
D80E20 + 1% Oleic Acid	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
D70E30 + 1% Oleic Acid	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
D90E10 + 1% Isopropanol	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable
D90E10 + 3% Isopropanol	Stable / Partially stable	Partially stable / Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable
D90E10 + 5% Isopropanol	Stable	Stable	Stable	Stable	Stable	Partially stable	Partially stable	Partially stable	Not stable
D80E20 + 5% Isopropanol	Stable	Stable	Stable	Partially stable	Partially stable	Partially stable	Partially stable	Not stable	Not stable
D80E20 + 7% Isopropanol	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable
D70E30 + 7% Isopropanol	Stable	Stable	Stable	Stable	Stable / Partially stable	Partially stable	Partially stable	Not stable	Not stable
D90E10 + 1% Ethylene Acetate	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable
D90E10 + 3% Ethylene Acetate	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable
D90E10 + 5% Ethylene Acetate	Partially stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable	Not stable
D90E10 + 7% Ethylene Acetate	Stable	Stable	Stable	Stable	Stable	Stable	Stable / Partially stable	Partially stable	Not stable

Stable (Homogeneous blend)	**Not stable (Heterogeneous mixture)**
Partially stable	

Table 2 The physical and thermal properties of diesel, DEE, ethanol, and oleic acid

Properties	Diesel	DEE	Ethanol	Oleic acid	Test method
Density (kg/m^3)	834	715	786	898	ASTM D1298
Calorific value (mJ/kg)	45.7	33.88	29.31	38.66	ASTM D240
Viscosity at 40 °C (cst)	3.91	0.24	1.057	19.92	ASTM D445
Cetane number	48	125	5	57.1	ASTM D613
Auto-ignition temperature °C	212	164	364	365	ASTM D8211
Oxygen content (%)	0	21.8	34.35	12.82	ASTM D5292
Flashpoint °C	54	− 38	16.65	188	ASTM D93

Result and discussion

Performance characteristics

Brake specific energy consumption

Figure 4 shows the variation of brake specific energy consumption (BSEC) against the brake power (BP). Irrespective of the fuel used, increase in engine's load decreased the BSEC. This shows that better combustion takes place at higher load conditions. At all load conditions, diesel produces the least BSEC than other all blends. In general, BSEC of ethanol blends are higher than that of all other blends and diesel. This is mainly due to lower CV value of ethanol which results in consumption of high quantity of fuel. At peak load, BSECs of D90E10, D80E20, and D70E30 were 12.8 mJ/kW.hr, 13.1 mJ/kW.hr, and 13.4 mJ/kW.hr, respectively, which were 6.1%, 8.7%, and 10.3% higher than that of diesel. This may be due to lower CV value and high LHV of ethanol which results in inferior combustion. It was also noticed that with increase in the ethanol concentration in blend, there is an increase in the BSEC. This is because the higher ratio ethanol blend has lower CV value. BSECs of DEE-enriched D90E10, D80E20, and D70E30 were 12.3 mJ/kW.hr, 12.6 mJ/kW.hr, and 12.8 mJ/kW.hr, respectively, which were 0.7%, 1.7%, and 3.1% lower when compared with without DEE ethanol blends of D90E10, D80E20, and D70E30 respectively. In addition, BSEC of DEE-enriched ethanol blend D90E10 was 0.7%, 2.6%, and 6.6% lower than without DEE ethanol blend D90E10, D80E20, and D70E30 respectively at rated brake power condition. It was noticed that BSEC of DEE-enriched ethanol blend was slightly lower than that of the one without it. This reliable decrease in BSEC was due to the improvement in the chemical reaction between the molecules into constructive work. BSEC of DEE-enriched D90E10 was very close to diesel. This is mainly due to low density, inbuilt O2, and high CV value of DEE that improves the homogeneity of charge mixture which results in superior combustion as well as lesser fuel consumption (Nabi et al. 2019).

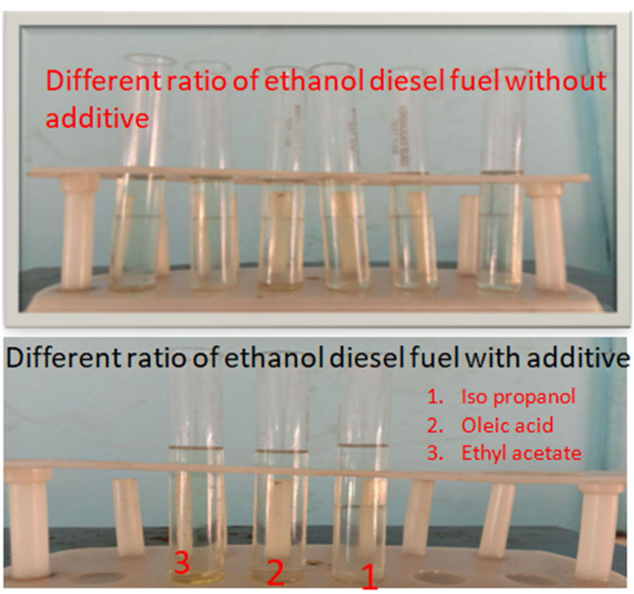

Fig. 1 Different ratio of ethanol-diesel blend with and without additive

Brake thermal efficiency

Figure 5 exhibits the variations of brake thermal efficiency (BTE) against the brake power for different blend ratios of

Table 3 Specification of the test engine

Description	Data
Manufacturer & model	Kirloskar Engines and LV1
Types of engines	Four strokes, constant speed, DI CI engine
Brake power at rated rpm	5.2 kW
Bore and stoke	87.5 mm and 110 mm
Compression ratio	17.5:1
Conventional injection pressure	220 bar
Conventional injection timing	21 bTDC
Injection nozzle	3-hole nozzle

ethanol and diesel. For all the blends ratios of ethanol-diesel, with an increase in the BP, the BTE increases. This is mainly due to better combustion occurred at higher load condition. Diesel fuel was noticed that highest BTE compared with other ethanol-diesel blends. At full load condition, BTEs of D90E10, D80E20, and D70E30 were 28.7%, 28.1%, and 27.0%, respectively, which were 5.7%, 7.5%, and 11.2% lower than that of diesel. This may be due to high LHV of ethanol and lower volatility. Thus, more amount heat energy is consumed by ethanol to produce flammable vapor in the ethanol blend compared with pure diesel, which results in inferior combustion. It was also noticed that BTE decreases with an increase in the percentage of ethanol in the blend. This may be due to the poor combustion quality of ethanol and higher latent heat of vaporization of ethanol. With an increase in the blend ratios of ethanol in the blend beyond 30%, engine vibration was noticed. This may be due to lesser cetane number and CV of ethanol which result in more fuel being burnt at diffusion phase. Similar result was noticed in previous studies investigated with ethanol blends (Alptekin 2017). On the other hand, BTE of DEE-enriched ethanol blend D90E10 was 0.7%, 2.6%, and 6.6% higher than without DEE ethanol blend D90E10, D80E20, and D70E30 respectively at rated brake power condition. This shows that the addition of diethyl ether has a great influence on the ethanol blend. This is mainly due to superior volatility, inbuilt O2, and calorific value of DEE that enhance the mixing rate of A/F composition which in turn give better combustion efficiency. At peak load condition, the BTEs of DEE-enriched D90E10, D80E20, and D70E30 blends were 0.7%, 1.7%, and 3.1% higher when compared with their receptive blends without DEE. Increase in ethanol concentration in blends decreases the BTE. This is attributed to an account of higher concentration of ethanol which reduce the heat content blends that results in more fuel accumulated in the chamber and produce inferior combustion (De Menezes et al. 2006).

Emission characteristics

Oxides of nitrogen

Figure 6 shows the deviation of NO_x emission against brake power. Irrespective of the fuel, increase in the brake power increases the NO_x emission. This is because at higher load condition, the combustion temperature increases and nitrogen reacts at a temperature above 1300 °C. The better combustion efficiency, the higher the NO_x emission produced. At full load condition, NO_x of D90E10, D80E20, and D70E30 were 765 ppm, 725 ppm, and 680 ppm, respectively, which were 6.9%, 11.8% and 17.2% lower than that of diesel. It is evident that with an increase in the percentage of ethanol in the blend the combustion temperature and NO_x emission decrease. This is mainly due to high LHV of ethanol which absorbs considerable amount heat in the combustion chamber, resulting in

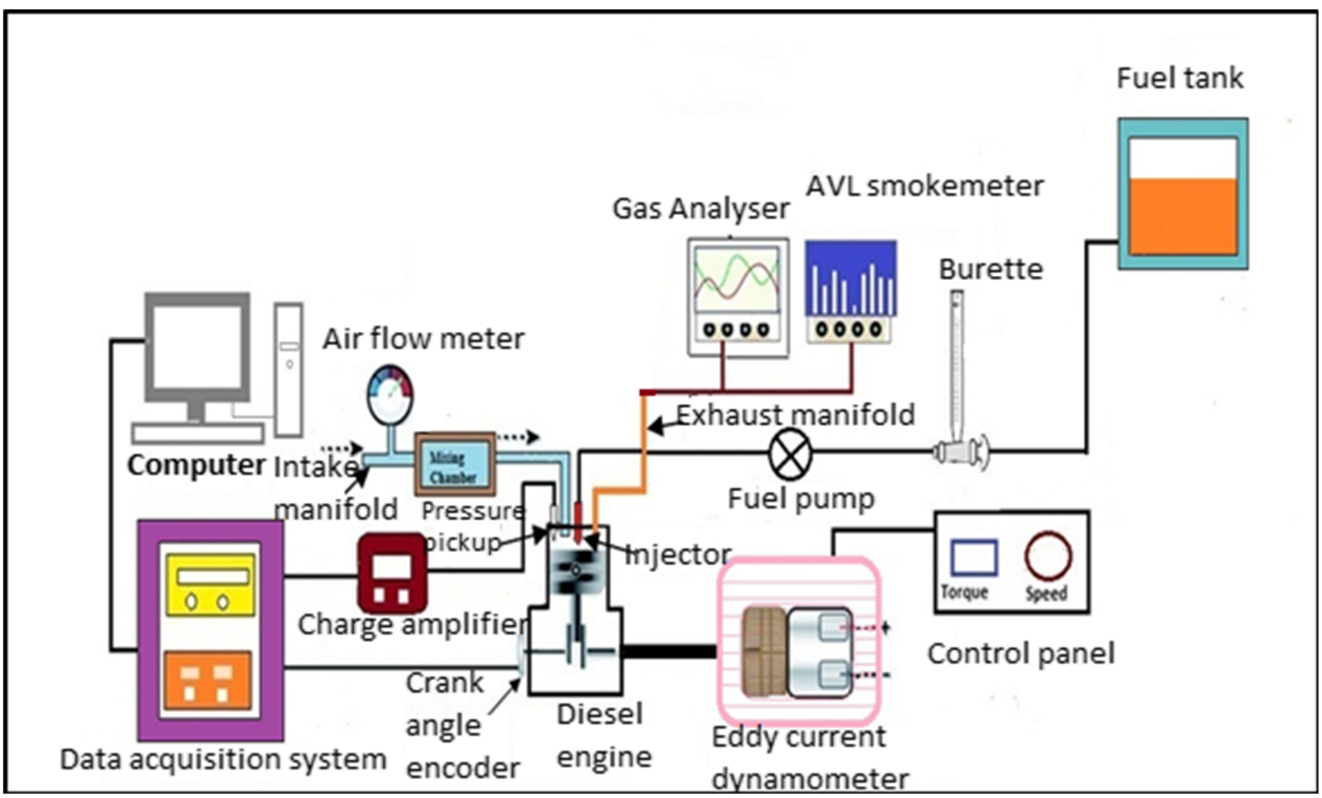

Fig. 2 Schematic diagram of the engine test rig

lower combustion temperature. Thus, the cooling effect of ethanol turns in lower combustion temperature inside the cylinder that results in lower NO_x emission. At the same time, NO_x of DEE-enriched D90E10, D80E20, and D70E30 were 774 ppm, 755 ppm, and 700 ppm, respectively, which were 5.8%, 8.1%, and 14.8% lower than that of diesel. In addition, NO_x emission of DEE-enriched ethanol blend was noticed to be 3% higher when compared with the blend without DEE. Fast combustion of DEE might result in higher combustion temperature that results in higher NO_x emission. This may attribute to high cetane rating and volatility feature of DEE which lead to enhance the combustion temperature that results in higher NO_x formation. Similar result was observed in previous work with ethyl alcohol-biodiesel blends (Parthasarathy et al. 2014).

Carbon monoxide

The variation of carbon monoxide (CO) emission across different brake powers is shown in Fig. 7. The CO emissions mainly depend upon the physicochemical properties of the fuel. At full load condition, CO of D90E10, D80E20, and D70E30 was 0.12%vol., 0.125%vol., and 0.129%vol., respectively, which were 5.8%, 9.6%, and 12.4% higher than that of diesel. It was noticed that ethanol blend has shown higher CO emission compared with other blends. This is because the low cetane number and high LHV of ethanol lead to higher ignition delay period, which results in partial combustion. Thus, deterioration of ethanol combustion might be responsible for the production of higher CO emission. In addition, ethanol has lower energy density. Thus, rich-mixture zone could be responsible for incomplete combustion that turns into higher CO formation. At the same time, CO emission of DEE-enriched ethanol blend D90E10 was 2.5%, 6.4%, and 9.3% lower than without DEE ethanol blend D90E10, D80E20, and D70E30 respectively at rated brake power condition. The reduction in CO emission of DEE-enriched ethanol blends could be due to lesser carbon fraction that results in improved combustion. Superior evaporation feature and inbuilt oxygen of DEE might raise the oxygen availability inside cylinder that results in improved oxidation of CO and enhance the combustion efficiency. Moreover, the time period of oxidation of ethanol is the factor controlling the OH radicals, which is encouraging the conversion of CO to CO_2 and minimizes the CO formation. Similar result was noticed in previous studies investigated with ethanol blends (Parthasarathy et al. 2019). Moreover, DEE-enriched ethanol blends of D90E10, D80E20, and D70E30 showed 2.5%, 4%, and 4.6% lower CO emission than without DEE ethanol blends of D90E10, D80E20,

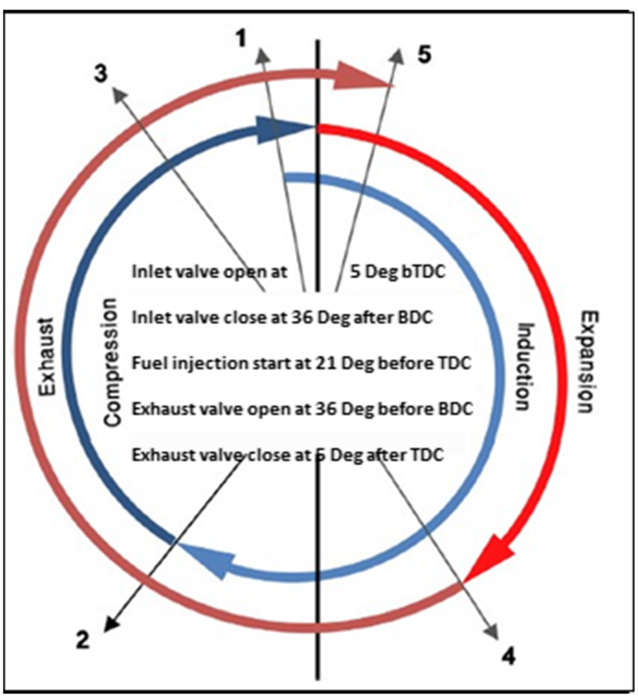

Fig. 3 Valve timing diagram used for this research

Table 4 Gas analyzer specification

Description	Data
Make	AVL Di gas analyzer
Measured gas	HC, CO, CO_2, O_2, NOx
Ranges	
HC	0 to 10000 ppm
CO	0 to 10%
CO_2	0 to 20%
O_2	0 to 25%
Accuracy/performance	
HC	12 ppm
CO	0.06%
CO_2	0.50%
O_2	0.10%

Table 5 The accuracy of the measured variable and calculated variable

Measured variable	Accuracy (±)
Torque (*T*)	1.0
Speed (*N*)	0.5
Fuel consumption (*g*)	0.1
Unburnt hydrocarbon (UBHC)	1.0
Carbon monoxide (CO)	0.7
Smoke opacity	1.1
Cylinder pressure (CP)	0.3
Oxides of nitrogen (NO_x)	1.4
Calculated variable	Accuracy (±)
BSEC	0.5
BTE	0.7

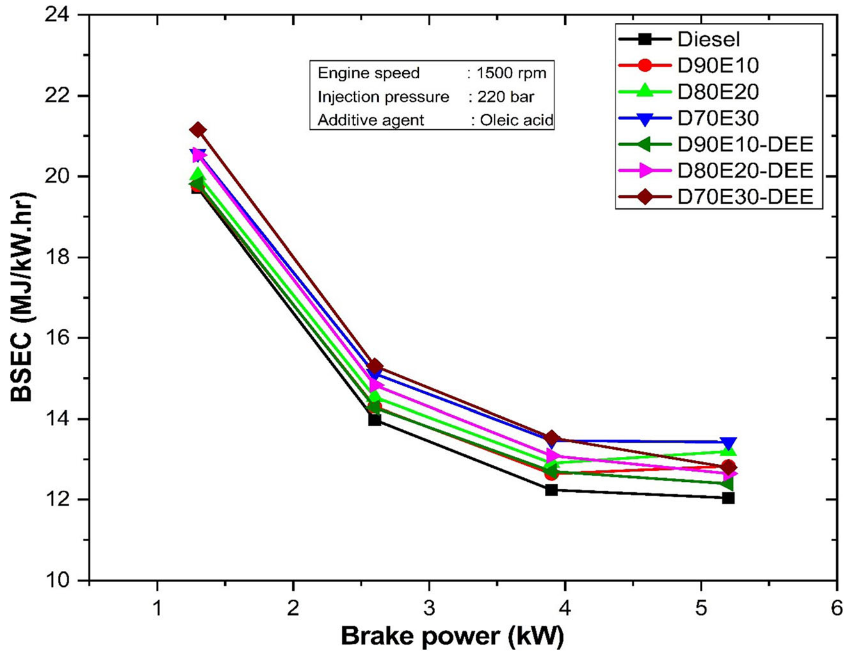

Fig. 4 Comparison of BSEC with BP of an engine at various ethanol blend

and D70E30 at rated brake power of 5.2 kW. The availability of O_2 molecules in DEE ethanol blends improves the combustion reaction which leads to superior combustion and thereby reduction of emission formation. While increasing the ethanol concentration in blends from 10 to 30%, the CO emission was gradually increased due to lower post-combustion temperature that results in restriction of promotion of CO emission.

Unburned hydrocarbon

Figure 8 illustrates the difference of unburned hydrocarbon (UBHC) emission with respect to brake power for ethanol-diesel blends. Generally, the formation of UBHC emissions is an effect of inferior combustion; nevertheless, complete combustion is achieved for lower UBHC emission. From the

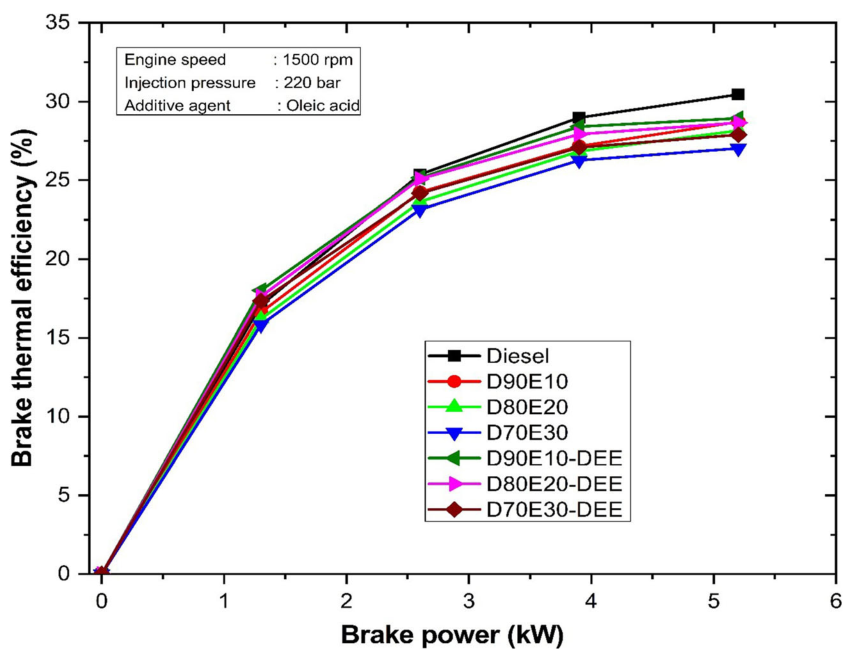

Fig. 5 Comparison of BTE with BP of an engine at various ethanol blend

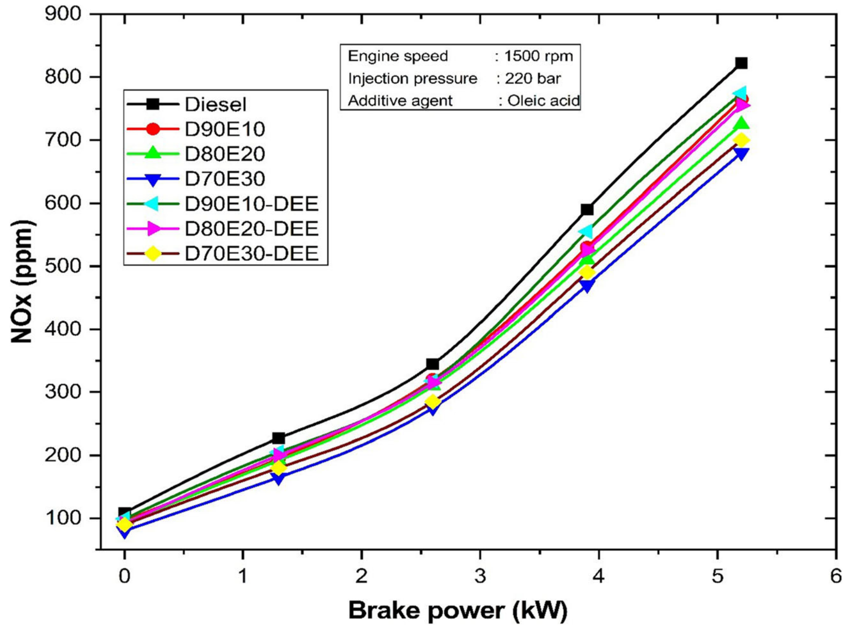

Fig. 6 Comparison of NO_x with BP of an engine at various ethanol blends

results, UBHC emission drastically increased for ethanol-diesel blends compared with that for diesel at full load condition. At full load condition, UBHCs of D90E10, D80E20, and D70E30 were 54 ppm, 57 ppm, and 61 ppm, respectively, which were 3.7%, 8.7%, and 14.7% higher than that of diesel. This is mainly due to the combined effect of lesser energy content of ethanol and higher latent of vaporization of ethanol which leads to higher mass of the fuel to be injected in the cylinder that results to form a rich-mixture zone. Thus, rich-mixture zone and less CN of ethanol lead to increase in the ID period that results in inferior combustion and formation of higher UBHC emission. In addition, high LHV of ethanol absorbs more amount of heat inside the combustion chamber which could have reduced the combustion temperature, leading to higher UBHC emission. On the other side, UBHC emission of DEE-enriched ethanol blend D90E10 was 1.8%, 7.0%, and 13.1% lower than without DEE ethanol blend D90E10, D80E20, and D70E30 respectively at rated brake power condition. The results noticed that DEE-enriched ethanol blends have slightly reduced the UBHC emission compared with ethanol-diesel blend. The lower UBHC emission for DEE-enriched ethanol blend has an evidence of improved combustion as a result of enhanced oxidation reaction. Thus, DEE might take part in prolonged oxidation, which results in

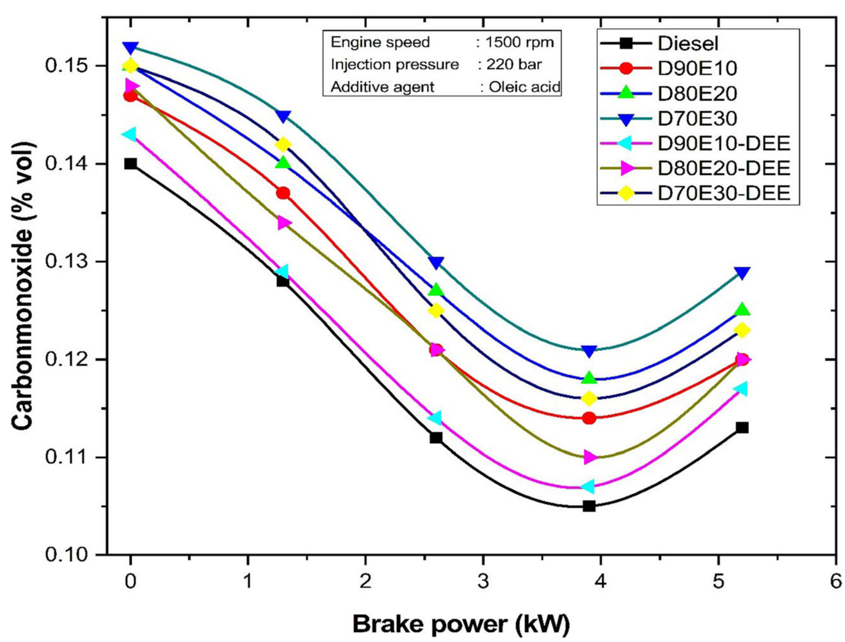

Fig. 7 Comparison of CO with BP of an engine at various ethanol blends

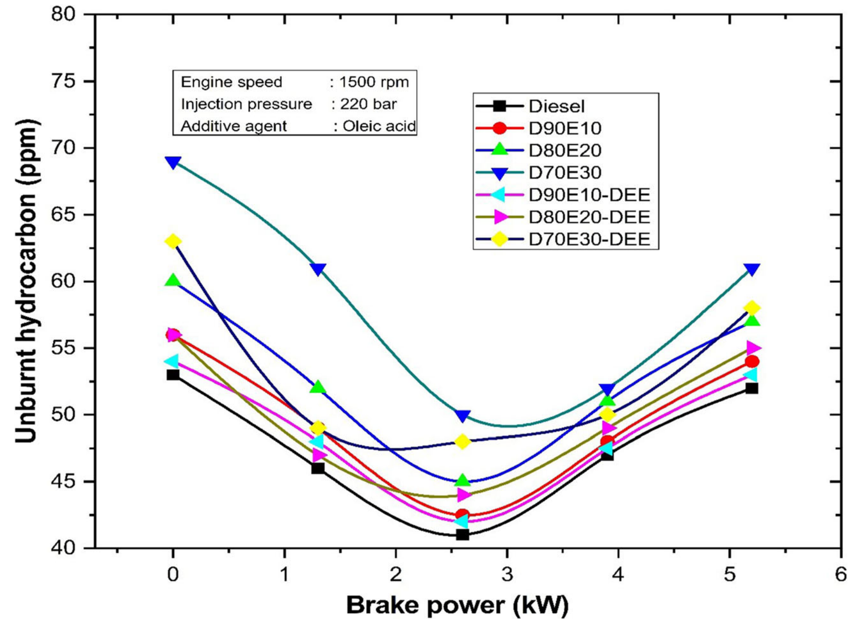

Fig. 8 Comparison of UBHC with BP of an engine at various ethanol blends

improved performance and lower UBHC formation. Moreover, DEE-enriched ethanol blends of D90E10, D80E20, and D70E30 showed 1.8%, 3.5%, and 4.9% UBHC emission than without DEE ethanol blends of D90E10, D80E20, and D70E30 at rated brake power of 5.2 kW. This is caused by the positive impact of DEE addition and the influence of better oxidation and lowered fuel-rich zone, whereas an increase in ethanol concentration in ethanol blend gradually increase UBHC due to more fuel accumulation rate, rich zone formation, and lower combustion temperature which results in higher UBHC formation (Parthasarathy et al. 2014).

Smoke

Smoke emissions of DEE and ethanol blends were found to be slightly increased than that of diesel (see Fig. 9). Increase in load conditions increases the smoke emission for all the test fuels. At peak load condition, smoke of D90E10, D80E20, and D70E30 was 61 HSU, 68 HSU, and 71 HSU, respectively, which was 9.8%, 19.1%, and 22.5% higher than that of diesel. This is mainly due to lesser CV of ethanol and rich fuel zone that result in lesser combustion temperature and more smoke formation. DEE-enriched ethanol blends of D90E10, D80E20, and D70E30 showed 4.9%, 5.8%, and 3.4% lower

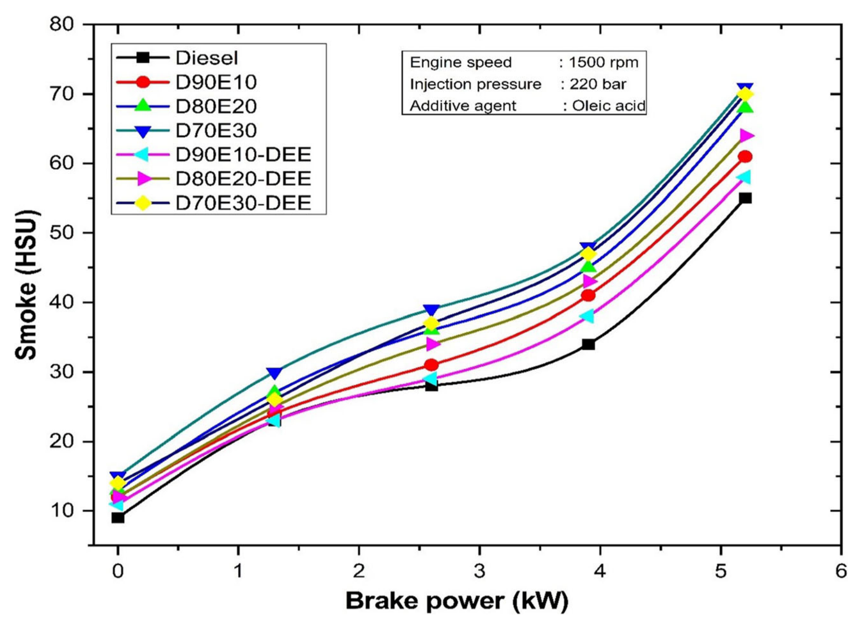

Fig. 9 Comparison of smoke with BP of an engine at various ethanol blends

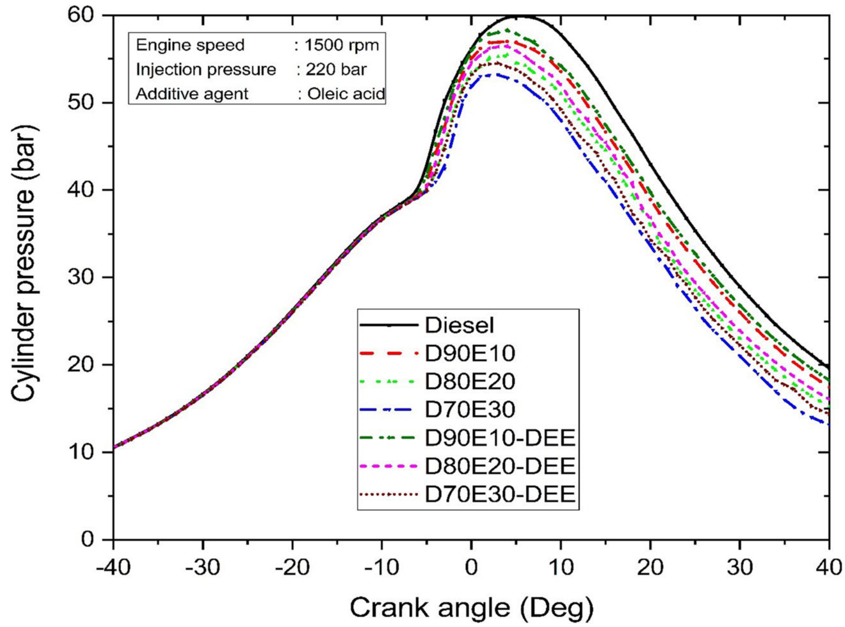

Fig. 10 Variation of cylinder pressure across different ethanol blends

smoke emission than without DEE ethanol blends of D90E10, D80E20, and D70E30 respectively. Increasing the ethanol concentration tends to increase the smoke emission for all test fuels due to low CV value of ethanol tends to admitted more amount of fuel in the cylinder which results in rich-mixture region and incomplete combustion. Smoke emission of DEE-enriched ethanol blend D90E10 was 4.9%, 14.7%, and 18.3% lower than without DEE ethanol blend D90E10, D80E20, and D70E30 respectively. It could be noticed that DEE-enriched ethanol blends have slightly reduced the smoke emission compared with ethanol-diesel blend. Reduction of smoke emission for DEE-enriched ethanol blend could be attributed to enhancing the combustion temperature and complete combustion. This is due to high cetane number and volatility of DEE, which are known for improving the combustion and minimizing the smoke emission. A similar result was observed in previous work with diesel blends (Qi et al. 2011).

Combustion characteristics

Cylinder pressure

Cylinder pressure is mainly dependent on the quantity of fuel burned throughout the uncontrolled combustion phase (rapid combustion stage) in CI engine. Figure 10 exposes the

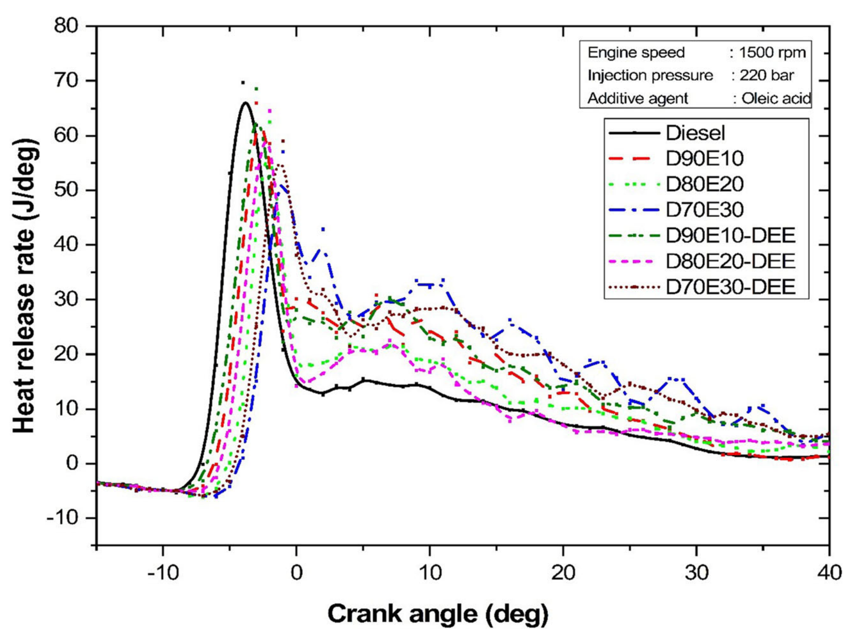

Fig. 11 Variation of heat release rate across different ethanol blends

variation of cylinder pressure for DEE and ethanol blends at peak load conditions. The peak pressure for diesel, D90E10, D80E20, and D70E30 at full load condition was 59.8 bar, 56.9 bar, 55.4 bar, and 53.2 bar, respectively. It was noticed that ethanol-diesel blends showed lower cylinder pressure compared with diesel fuel. This is mainly due to the lower cetane number and high LHV of ethanol compared with that of diesel. This may be attributed to increase the ignition delay period and lower combustion temperature which lead to produce lesser cylinder pressure. Cylinder pressure for DEE-enriched ethanol blends D90E10, D80E20, and D70E30 are 58.2 bar, 56.5 bar, and 54.4 bar, respectively. The DEE-enriched ethanol blend improved the homogeneity of A/F mixture, which results in lesser ignition delay and rapid combustion process. At higher load conditions, DEE-enriched D90E10, D80E20, and D70E30 blends had 2.2%, 1.8%, and 2.4% higher cylinder pressure when compared with the blends without DEE. This is because the adequate oxygen present in DEE enhances the combustion process. In addition, high energy content and cetane number of DEE leads to improvement in cylinder temperature, which results in higher cylinder pressure.

Heat release rate

As shown in Fig. 11, DEE-enriched ethanol blends had an improved combustion and HRR when compared with the blends without blends DEE. Fuel property has a great influence over the heat release rate and pressure-rise inside the combustion chamber. Diesel produces higher HRR when compared with other test fuels. This is because of better physical and thermal property of diesel which enhances the HRR. The heat release rate for diesel, D90E10, D80E20, and D70E30 at peak load was 69.6, 66.9, 62.5, and 57.0 J/°CA, respectively. With increase in the percentage of ethanol in the blend, HRR decreases as result of increase the ignition delay period. This is because of lesser cetane number and lower energy content of ethanol. At higher load conditions, the HRRs of DEE-enriched D90E10, D80E20, and D70E30 blends were respectively, 2.5 %, 2.2%, and 2.6% higher when compared with their receptive blends without DEE. It was noticed that the combustion of DEE-enriched ethanol blends was superior to other blends. It was also noticed that the start of combustion of DEE-enriched blend was earlier than that of other ethanol blends. This is attributed to the lower LHV and higher cetane number of DEE could attribute to shorter ID. In addition, oxygen-enriched ethanol and DEE blends produce more complete combustion, which results in superior primary combustion phase and higher HRR compared with other ethanol blends.

Conclusions

Based on the experimental investigation carried out on CI engine fueled with different blend ratios of ethanol-diesel blends, the author tested the blends with different additives to enhance stability of ethanol blends. The important findings of this research work have been notified as follows:

- Ethanol is immiscible with diesel without additive. Usage of isopropanol, oleic acid, and ethylene acetate improves the homogeneity of the ethanol-diesel blend. It was found that oleic acid produces the best homogeneity among the other additive.
- Through the addition of ethanol into diesel, the BTE was decreased and BSEC was increased. With an increase in the percentage of ethanol in the blend, the BTE was drastically reduced and the engine consumes more fuel. This is attributed to lower energy density of ethanol that results in the consumption of higher fuel quantity.
- The BTE of DEE-enriched ethanol blends was higher than that of blends without DEE. This improvement was due to the enrichment in the fuel properties which ensures better combustion efficiency.
- NO_x emission drastically decreased for all ethanol blends compared with diesel operation. This is mainly due to the cooling effect of ethanol which turns to lower down the combustion temperature inside the cylinder that results in lower NO_x emission. DEE-enriched blends exhibited higher NO_x emission than other ethanol blends. This was attributed to enhance the combustion efficiency which results in higher combustion temperature.
- The CO and UBHC emissions of ethanol blends were higher compared with those of diesel fuel. In contrast, DEE blends noticed lower CO and UBHC emission compared with that of ethanol blends. This may be due to higher LHV and CN of DEE-enhanced blends which give out complete combustion that results in higher flame temperature.
- Smoke emission for all ethanol blends increased when the ethanol percentage increased in blends according to diesel. On the other hand, DEE blends were observed to emit low smoke. This is mainly due to high cetane rating of DEE which narrows down the ignition delay period which results in diminishing of the diffusion combustion phase.
- Blends with DEE showed better combustion characteristics compared with ethanol blends. High energy content and inbuilt O_2 with DEE exhibited an excellent cylinder pressure and HRR value. The high CN of DEE resulted in the speed up at the start of combustion (i.e., lesser ignition delay) which results in enhanced premixed combustion and better cylinder temperature. Based on the

experimental study, it was concluded that DEE blends showed better performance and combustion characteristics.

Future prospects

In the present study can be implemented in the dual fuel operation for further reduction of smoke emission. Dual fuel mode of operation can be parallelly minimizing the smoke and NO_x emission. The dual fuel mode can be investigated fueled with blend diesel-ethanol as a main energy source and DEE inducted along with air as secondary source of energy. This can further enhance the performance of engine. Moreover, experiment studies can investigate the effect of various nanoadditives with ethanol biodiesel blends in CI engine. DEE blends should be tested under different operating conditions in further experiments.

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Authors' contributions RS conducted investigation on blends stability. PM carried out to test engine fueled with DEE-enriched ethanol blend. GGG examined the brief literature review on influence of ethanol blend in diesel fuel. BD analyzed the combustion characteristics of engine. All authors read and approved the final manuscript.

Availability of data and materials The source of data and materials of this study is available from the corresponding author, upon reasonable request.

Compliance with ethical standards

Ethical approval and consent to participate Ensure that all the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

Competing interests The authors declare that they have no competing interests.

References

Alptekin E (2017) Evaluation of ethanol and isopropanol as additives with diesel fuel in a CRDI diesel engine. Fuel 205:161–172. https://doi.org/10.1016/j.fuel.2017.05.076

Bragadeshwaran A, Kasianantham N, Ballusamy S, Tarun KR, Dharmaraj AP, Kaisan MU (2018) Experimental study of methyl tert-butyl ether as an oxygenated additive in diesel and Calophyllum inophyllum methyl ester blended fuel in CI engine. Environ Sci Pollut Res 25(33):33573–33590. https://doi.org/10.1007/s11356-018-3318-y

Chang YC, Lee WJ, Wu TS, Wu CY, Chen SJ (2014) Use of water containing acetone-butanol-ethanol for NOx-PM (nitrogen oxide-particulate matter) trade-off in the diesel engine fueled with biodiesel. Energy 64(x):678–687. https://doi.org/10.1016/j.energy.2013.10.077

De Menezes EW, Da Silva R, Cataluña R, Ortega RJC (2006) Effect of ethers and ether/ethanol additives on the physicochemical properties of diesel fuel and on engine tests. Fuel 85(5–6):815–822. https://doi.org/10.1016/j.fuel.2005.08.027

Ferreira VP, Martins J, Torres EA, Pepe IM, De Souza JMSR (2013) Performance and emissions analysis of additional ethanol injection on a diesel engine powered with a blend of diesel-biodiesel. Energy Sustain Dev 17(6):649–657. https://doi.org/10.1016/j.esd.2013.08.005

Gnanamoorthi V, Devaradjane G (2015) Effect of compression ratio on the performance, combustion and emission of di diesel engine fueled with ethanol–Diesel blend. J Energy Inst *88*(1):19–26. https://doi.org/10.1016/j.joei.2014.06.001

Górski K, Przedlacki M (2014) Evaluation of the influence of diethyl ether (DEE) addition on selected physicochemical properties of diesel oil and ignition delay period. Energy Fuel 28(4):2608–2616. https://doi.org/10.1021/ef4025036

Guo L, Yan YY, Tan M, Li H, Peng Y (2011) An experimental study on improving the ignition of ethanol-diesel blended fuel (EDBF). Chem Eng Commun 198(10):1263–1274. https://doi.org/10.1080/00986445.2010.525208

Hariz HB, Takriff MS (2017) Palm oil mill effluent treatment and CO2 sequestration by using microalgae—sustainable strategies for environmental protection. Environ Sci Pollut Res 24(25):20209–20240. https://doi.org/10.1007/s11356-017-9742-6

Ibrahim A (2018) An experimental study on using diethyl ether in a diesel engine operated with diesel-biodiesel fuel blend. Eng Sci Technol Int J 21(5):1024–1033. https://doi.org/10.1016/j.jestch.2018.07.004

Janakiraman S, Lakshmanan T, Chandran V, Subramani L (2020) Comparative behavior of various nano additives in a DIESEL engine powered by novel Garcinia gummi-gutta biodiesel. J Clean Prod 245:118940. https://doi.org/10.1016/j.jclepro.2019.118940

Liu H, Wang X, Wu Y, Zhang X, Jin C, Zheng Z (2019) Effect of diesel/PODE/ethanol blends on combustion and emissions of a heavy duty diesel engine. Fuel 257(June):116064. https://doi.org/10.1016/j.fuel.2019.116064

Nabi MN, Rahman SMA, Bodisco TA, Rasul MG, Ristovski ZD, Brown RJ (2019) Assessment of the use of a novel series of oxygenated fuels for a turbocharged diesel engine. J Clean Prod 217:549–558. https://doi.org/10.1016/j.jclepro.2019.01.249

Kazemi Shariat Panahi, H., Dehhaghi, M., Kinder, J. E., & Ezeji, T. C. (2019). A review on green liquid fuels for the transportation sector: a prospect of microbial solutions to climate change. Biofuel Research Journal, 6(3), 995–1024. https://doi.org/10.18331/BRJ2019.6.3.2

Parthasarathy M, Lalvani JIJR, Prakash E, Jayaraj S, Annamalai K (2014) Experimental investigation on combustion and emission characteristics of modified piston in an IDI diesel engine fueled with ethyl alcohol. In Adv Mater Res 984–985:873–877. https://doi.org/10.4028/www.scientific.net/AMR.984-985.873

Parthasarathy M, Ramkumar S, Isaac Joshua Ramesh Lalvani J (2019) Influence of various flow rates of CNG in CI engine with blend of Tamanu methyl ether and ethanol. Int J Veh Struct Syst 11(2). https://doi.org/10.4273/ijvss.11.2.06

Parthasarathy M, Ramkumar S, Isaac JoshuaRamesh Lalvani J, Elumalai PV, Dhinesh B, Krishnamoorthy R, Thiyagarajan S (2020) Performance analysis of HCCI engine powered by tamanu methyl ester with various inlet air temperature and exhaust gas recirculation ratios. Fuel 282(March):118833. https://doi.org/10.1016/j.fuel.2020.118833

Qi DH, Chen H, Geng LM, Bian YZ (2011) Effect of diethyl ether and ethanol additives on the combustion and emission characteristics of biodiesel-diesel blended fuel engine. Renew Energy 36(4):1252–1258. https://doi.org/10.1016/j.renene.2010.09.021

Ramalingam K, Balasubramanian D, Chellakumar PJTJS, Padmanaban J, Murugesan P, Xuan T (2020) An assessment on production and engine characterization of a novel environment-friendly fuel. *Fuel 279*(April):118558. https://doi.org/10.1016/j.fuel.2020.118558

Shaafi T, Velraj R (2015) Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel-soybean biodiesel blend fuel: combustion, engine performance and emissions. Renew Energy 80:655–663. https://doi.org/10.1016/j.renene.2015.02.042

Torres-Jimenez E, Jerman MS, Gregorc A, Lisec I, Dorado MP, Kegl B (2011) Physical and chemical properties of ethanol-diesel fuel blends. Fuel 90(2):795–802. https://doi.org/10.1016/j.fuel.2010.09.045

Yesilyurt MK, Aydin M (2020) Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends. Energy Convers Manag 205(October 2019):112355. https://doi.org/10.1016/j.enconman.2019.112355

Yilmaz N, Vigil FM, Benalil K, Davis SM, Calva A (2015) Erratum: Effect of biodiesel-butanol fuel blends on emissions and performance characteristics of a diesel engine (Fuel (2014) (46-50)). Fuel 139:781. https://doi.org/10.1016/j.fuel.2014.09.019