

A review study on the using of diethyl ether in diesel engines: effects on smoke and PM emissions

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ABSTRACT

This study was compiled from the results of various researches performed on using diethyl ether as a fuel or fuel additive in diesel engines. Three different techniques are used for the reduction of the harmful exhaust emissions of diesel engines. The first technique for the reduction of harmful emissions is improved the combustion by modification of engine design and fuel injection system, but this process is expensive and time consuming. The second technique is the using various exhaust gas devices like catalytic converter and diesel particulate filter. However, the use of these devices affects negatively diesel engine performance. The final technique to reduce emissions and also improve diesel engine performance is the use of various alternative fuels or fuel additives. The major pollutants of diesel engines are oxide of nitrogen (NO_x) and smoke or particulate matter (PM). It is very difficult to reduce NO_x and PM simultaneously in practice. Most of the researchers declare that the best way to reduce is the use of various alternative fuels i.e. natural gas, biogas, biodiesel or using the additives with alternative fuels or conventional diesel fuel. Therefore, it is very important that the results of various studies on alternative fuels or fuel additives are evaluated together to practice applications. Especially, this study focus on the use of diethyl ether in diesel engines as fuel or fuel additive in various diesel engine fuels. This review study investigates the effects of diethyl ether addition on the smoke and PM emissions.

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1. Introduction

Diesel engines are widely used in both light and heavy-duty vehicles [1]. They are reliable, robust and the most efficient internal combustion engines [2]. However, diesel engines are suffer form their high emission drawbacks like particulate matters (PM), total gaseous hydrocarbons (THC), nitrogen oxides (NO_x), sulfur oxides (SO_x) and smoke [3, 4]. It is seemed that the most suitable way to reduce of these emissions is the using of alternative fuels made from renewable sources instead of the commercial fuels [5]. However, complete replacement of fossil fuels with renewable alternative fuels will require to a comprehensive modification of the engine hardware and their combustion in the engine results in operational and technical limitations [6]. The fuel side modification techniques such as blending, emulsification and oxygenation are the easy way for emission reduction without any modification on the engine hardware. Modification of diesel fuel to reduce exhaust emission can be performed by increasing the cetane number, reducing fuel sulphur, reducing aromatic content, increasing fuel volatility and decreasing the fuel density to have the compromise

between engine performance and engine out emissions, one such change has been the possibility of using diesel fuels with oxygenates [7]. Among different alternative fuels, oxygenated fuel is a kind of alternative fuel. Diethylene glycol dimethyl ether (DGM), dimethoxy methane (DMM), dimethyl ether (DME), methyl tertiary butyl ether (MTBE), dibutyl ether (DBE), dimethyl carbonate (DMC), methanol, ethanol and diethyl ether (DEE) have played their role to reduce diesel emissions [7, 8, 9]. These fuels can either be used as a blend with conventional diesel fuel or pure. These additives can also be used in combination with biodiesel [10]. The presence of oxygen in the fuel molecular structure plays an important role to reduce PM and other harmful emissions from diesel engines. However, NO_x emissions can be reduced in some cases and be increased depending on the engine operating conditions [11, 12]. Especially, DEE is a suitable fuel for diesel engines due to it is a cetane improver besides an oxygenated fuel [13]. Therefore, this review study is devoted to use of DEE in diesel engines as fuel or fuel additive in various diesel engine fuels.

2. Properties of diethyl ether

Diethyl ether is the simplest ether expressed by its chemical formula $\text{CH}_3\text{CH}_2\text{-O-CH}_2\text{CH}_3$, consisting of two ethyl groups bonded to a central oxygen atom as seen in Fig. 1.

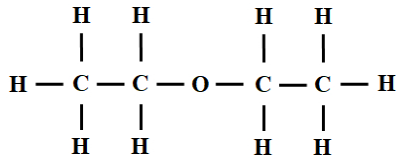


Figure 1. Diethyl ether chemical structure [3]

Diethyl ether (DEE) is regarded as one of the promising alternative fuels or an oxygen additive for diesel engines with its advantages of a high cetane number and oxygen content. DEE is liquid at the ambient conditions, which makes it attractive for fuel storage and handling. DEE is produced from ethanol by dehydration process as seen in Fig. 2 so it is a renewable fuel [14].

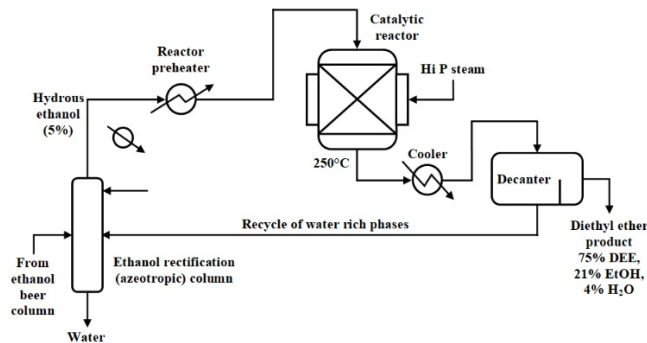


Figure 2. Production of diethyl ether from ethanol [14]

As shown in Table 1, DEE has several favorable properties, including exceptional cetane number, reasonable energy density, high oxygen content, low autoignition temperature and high volatility. Therefore, it can be assist to improving of engine performance and reducing the cold starting problem and emissions when using as a pure or an additive in diesel engines [14, 15].

Table 1. The main fuel properties of diesel fuel and DEE [15].

Property	Diesel	DEE
Chemical formula	C_xH_y	$\text{C}_4\text{H}_{10}\text{O}$
Molecular weight	190-220	74
Density of liquid at NTP* (kg/L)	~0.84	0.71
Viscosity at NTP* (cP)	2.6	0.23
Oxygen content (wt %)	-	21
Sulfur content (ppm)	~250	-
Boiling temperature ($^{\circ}\text{C}$)	180-360	34.6
Autoignition temperature in air ($^{\circ}\text{C}$)	315	160
Flammability limit in air (vol %)	0.6-6.5	1.9-9.5
Stoichiometric air-fuel ratio (AFR_s)	14.6	11.1
Heat of vaporization at NTP* (kJ/kg)	250	356
Lower heating value (MJ/kg)	42.5	33.9
Cetane number (CN)	40-55	125

*NTP: Normal temperature and pressure

There are some challenges with DEE such as storage stability, flammability limits and lower lubricity. Storage stability of DEE and DEE blends are of concern because of a tendency to oxidize, forming peroxides in storage. It is suggested that antioxidant additives may be available to prevent storage oxidation. Flammability limits for DEE as seen in Table 1 are broader than that of diesel fuel, but the rich flammability limit of DEE is in question [14].

3. Studies on diethyl ether in literature

There are a number of studies in literature on the use DEE in diesel engines as a fuel or fuel additive in various diesel engine fuels. For example; as pure, with diesel fuel, with diesel-ethanol blends, with diesel-ferric chloride blends, with diesel-kerosene blends, with diesel-acetylene gas dual fuel, with biogas, with liquefied petroleum gas, with diesel-natural gas dual fuel, with ethanol, with various biodiesel fuels, with biogas-biodiesel blends, with water-biodiesel emulsion fuel, with various biodiesel-diesel blends, with ethanol-biodiesel-diesel blends and methanol-biodiesel-diesel blends [16-113].

4. PM and smoke emissions

Rakopoulos et al declared that the soot emitted by all DEE-diesel blends was lower than neat diesel fuel. The reduction was higher for higher the percentage of DEE in the blend. This might be attributed to the engine running overall leaner, with the combustion being now assisted by the presence of oxygen in DEE even in locally rich zones, which seemed to have the dominating influence. This decrease in smoke emissions was significant for the higher load and modest for lower loads as seen in Fig. 3(a) [17]. Banapurmath et al declared that smoke is direct indication of incomplete combustion in the engine and is formed in fuel rich regions in the combustion chamber. Smoke emission was higher at low loads, which might be due to short combustion cycle at high speed, long delay period and

shortage of oxygen which might be due to improper mixing or usage of rich fuel. The smoke emissions were reduced with DEE blends. This might be due to overall leaning operation of the engine as the combustion was assisted by the presence of the fuel-bound oxygen of DEE. Additionally, high volatility of DEE had a remarkable effect on the reduction of smoke emissions, especially at high engine loads; hence DEE20 blend showed the lowest smoke emissions as seen in Fig. 3(b) [22].

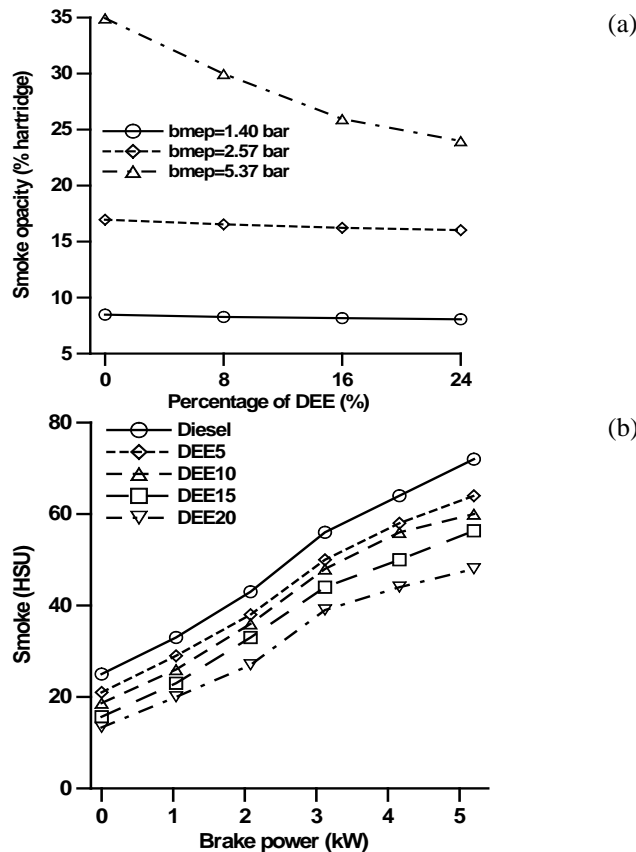


Figure 3. Effect of diethyl ether additive on smoke emissions of diesel fuel [17, 22]

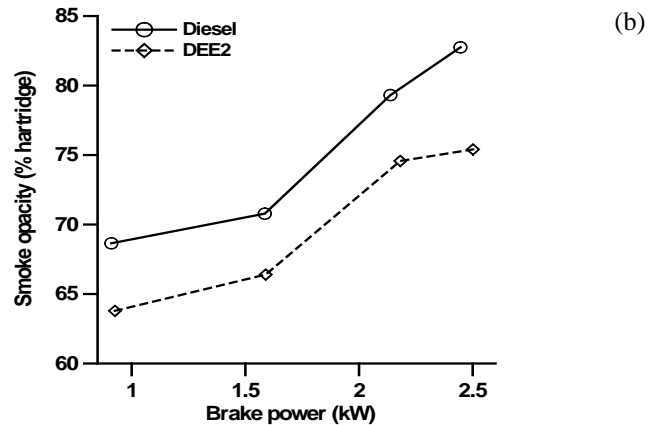
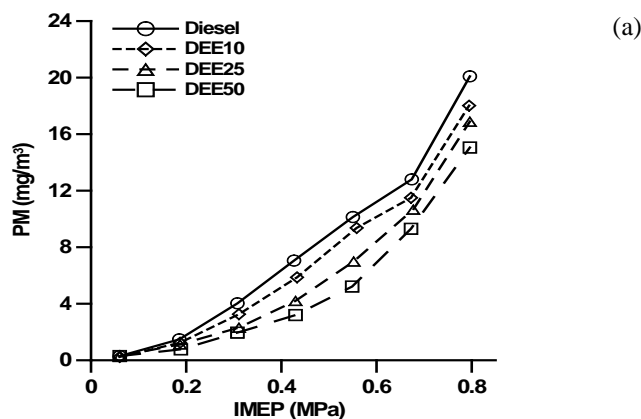


Figure 4. Effect of diethyl ether additive on PM emissions [23] and smoke emissions [28] of diesel fuel

Lee and Kim declared that diesel particulate matter (PM) consists principally of combustion generated carbonaceous material (soot) on which some organic compounds have absorbed. Unsaturated hydrocarbons, such as polycyclic aromatic hydrocarbons (PAHs) and acetylene, are the most likely precursors of soot particles. PM tended to increase with increasing engine load for all the tested fuels because the volume for fuel-rich regions became large as the amount of fuel injected increased with increased engine load. This resulted in high PM emissions due to the worsening air-fuel mixing in the combustion chamber. Also, diesel had the highest PM, which decreased with increasing DEE content as seen in Fig. 4(a). This might be attributed to the high volatility and the presence of fuel bound oxygen in DEE. DEE is more volatile and has a lower self-ignition temperature than pure diesel. So, DEE enabled better mixing of the air-fuel mixture and provided more complete combustion. The presence of fuel bound oxygen in the blended fuels created locally lean fuel-air mixture environments and aided in the oxidation of unsaturated hydrocarbons during the diffusion flame phase rather than allowing them to act as precursors of soot particles [23]. Saravanan et al declared that the incomplete combustion of the fuel hydrocarbon increases the smoke opacity. The increase of DEE in diesel fuel increased the smoke opacity. This might be due to the phase separation of the blend [24]. Balamurugan and Nalini declared that the addition of DEE with diesel decreased the smoke density appreciably as seen in Fig. 4(b). This was because of the increase in combustion efficiency and the release of more CO₂ due to increase in cetane number of the blend by blending of DEE with diesel [28]. Madhu et al declared DEE-diesel blends gave better smoke reduction which indicated that there was better combustion. Smoke emission showed minimum levels for DEE15, which was 17% less than diesel fuel. As the fuel injection pressure increased, smoke emission reduced. It was also found that with increase in composition of DEE at any injection pressure, the smoke levels were found reduced. DEE, being a volatile fuel could overcome poor mixing of the

fuel with air and led to improvement in diffusive combustion [29]. Cinar et al declared that smoke emissions were reduced with increasing in the premixed DEE fuel ratio. In HCCI-DI engine, premixed fuel charge was homogeneously introduced into the cylinder. Therefore, rich fuel regions in combustion chamber were minimized and formation of soot precursors was prevented. Also, DEE fuel was oxygenated and it had low carbon to hydrogen ratio. It had positive effect on the elimination of soot formation. Smoke emissions were decreased up to 76% with increase in the premixed fuel ratio of DEE as seen in Fig. 5(a) [32].

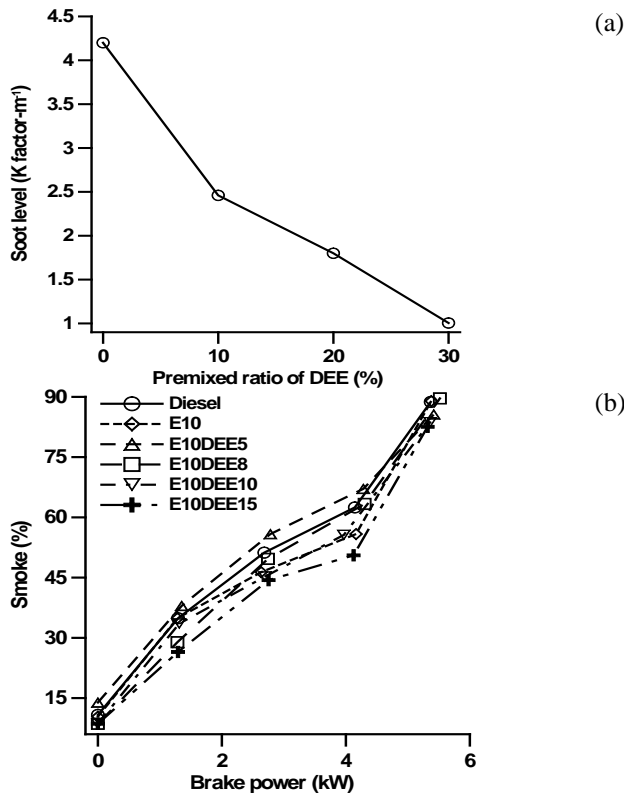


Figure 5. Effect of diethyl ether premixed ratio on smoke emissions of diesel fuel [32] and ethanol-diesel blend [33]

Iranmanesh declared that the general trend of smoke opacity displayed a reduction with addition of oxygenates as seen in Fig. 5(b) due to oxygen content in ethanol and DEE which helped in an improved combustion than neat diesel fuel. Since the smoke was produced mainly in the diffusive combustion phase, the addition of oxygenated fuel led to an improvement in diffusive combustion. On the other hand, enhancing the oxygen content in the charge, could overcome poor mixing of the fuel with air, which was responsible for smoke formation in diesel engines. E10DEE15 blend showed the lowest smoke opacity at all of the load conditions [33]. Sudhakar and Sivaprakasam declared that smoke density decreased for all test fuels while compare with diesel as seen in Fig. 6(a). The maximum decreased percentage 32 was achieved for 30% injection of DEE. This was due to the oxygen enrichment of ethanol and DEE improved reactions in

diffusion phase of combustion reflected in reduction in smoke density [35]. Sudhakar and Sivaprakasam declared that smoke density of E15 decreased. The increasing percentage of DEE injection without EGR decreased the smoke density. However, the increasing percentage of hot EGR was resulted increased smoke density than in the case of without EGR [36].

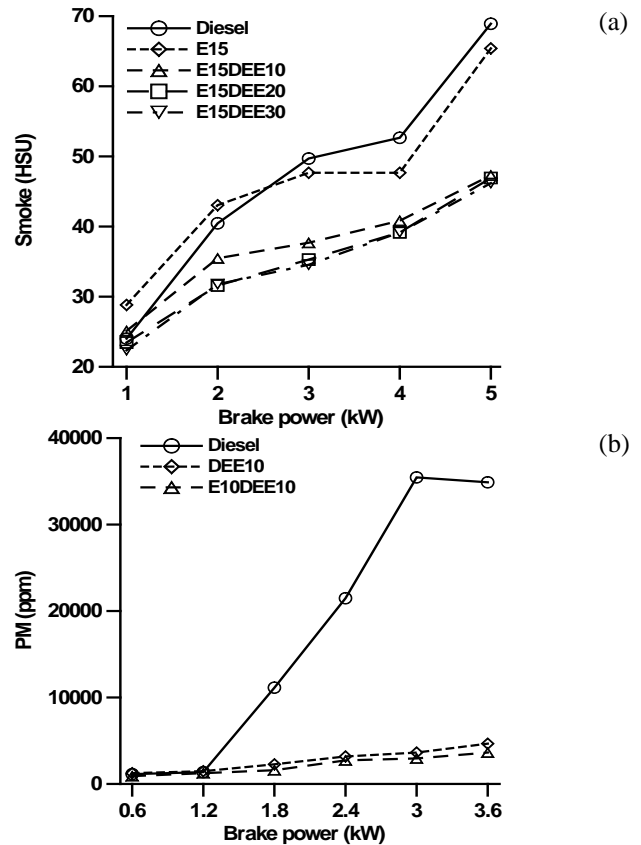


Figure 6. Effect of diethyl ether premixed ratio on smoke emissions of ethanol-diesel blend [35] and PM emissions of ethanol-diesel blend [37]

Paul et al declared that PM emission from the engine had drastically reduced with all the blends at medium and high load conditions. At low loads, diesel-DEE blends showed reduced or similar PM emission rates as compared to diesel. This might be due to lower in-cylinder temperature and pressure that reduced the quality of combustion. At medium and high load conditions, the PM emission from the engine decreased for all the tested fuel blends as seen in Fig. 6(b). The high cetane number and 21.6% oxygen content of DEE was advantageous to the combustion as the former reduced the ignition delay and the later helped in better combustion of the charge. As a result, the carbon and soot elements burned and reduced the PM emission. This was reflected in the drastic reduction in PM emission with diesel-DEE blends. It was also found that addition of ethanol further reduced the PM emission. This was because combustion of ethanol liberated the 'OH' radicals into the combustion chamber. These 'OH' radicals are instrumental in soot decomposition in diffusion

flame. Hence, with the increase of ethanol content in fuel, the PM emission reduced invariably [37]. Patnaik et al declared that the smoke opacity was reduced for DEE15 blend by 72% compared to diesel fuel at higher engine load as seen in Fig 7(a). The blend of DEE advanced the combustion by reducing ignition delay which led to increase in combustion time resulting in the reduction of soot formation. The molecular oxygen content of DEE depromoted the formation of smoke during the diffusion phase of combustion [41]. Rakopoulos declared that the soot emitted by the DEE blends was lower than those of the neat biodiesel and diesel as seen in Fig. 7(b). This might be attributed to the presence of extra fuel bound oxygen in the blends even at locally fuel rich zones [50].

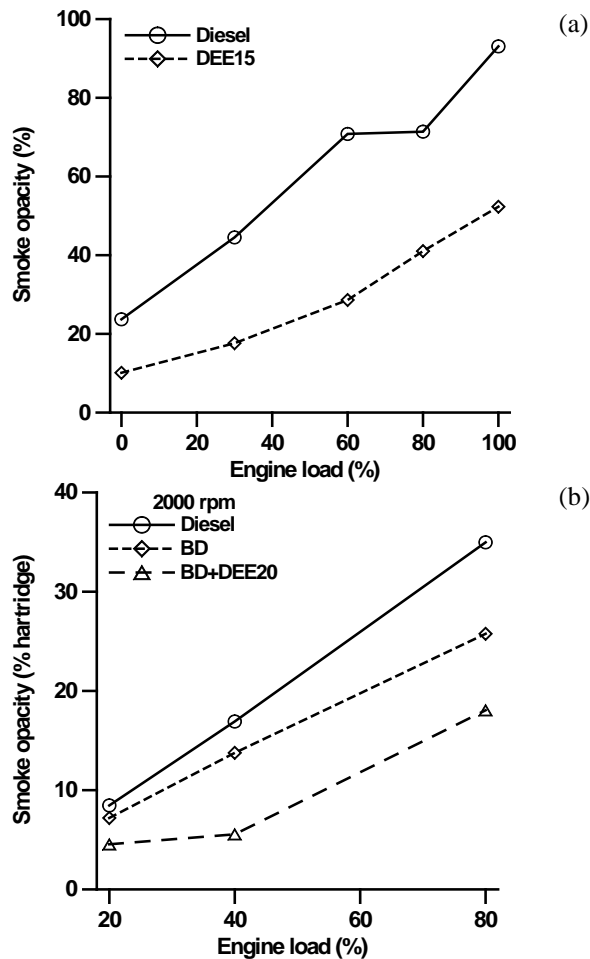


Figure 7. Effect of diethyl ether on smoke emissions of diesel fuel [41] and biodiesel fuel [50]

Jawre and Lawankar declared that smoke intensity with diesel fuel was higher than biodiesel and DEE blends as seen in Fig. 8(a). Smoke was formed due to incomplete combustion of fuel. Oxygen content in biodiesel was higher than diesel fuel. Improved and complete combustion could be the reasons for obtaining lower smoke emission values with biodiesel. Addition of DEE to biodiesel also improved oxygen content and reduced viscosity. Smoke emission with DEE10 and DEE15 blend gave lower value smoke and it was lower by

21% and 28% compared to biodiesel [55]. Sivalakshmi and Balusamy declared that the smoke intensity decreased by 10% for DEE5 blend comparing to that of biodiesel as seen in Fig. 8(b). Smoke was formed at rich region, the improvement in spray atomization and fuel-air mixing with the addition of diethyl ether decreased the rich mixture region and decreased the smoke emission. However, in case of DEE10 and DEE15 blends, the smoke intensity seemed to increase but it was still lower than that of biodiesel and diesel. This might be due to phase separation of the blend, which resulted in incomplete combustion of fuel [59].

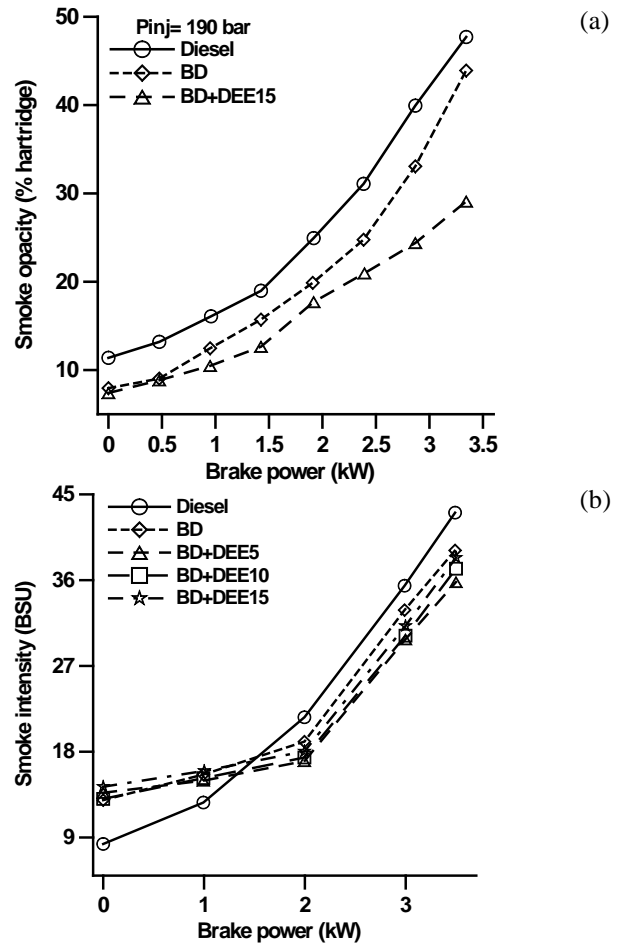


Figure 8. Effect of diethyl ether on smoke emissions of biodiesel fuel [55, 59]

Rajan et al declared that the smoke emission decreased with increase of DEE in the blends with biodiesel at full load as seen in Fig. 9(a). The maximum smoke emissions for 10% and 15% DEE were 3.4 BSU and 3.2 BSU, respectively, whereas the same for diesel and neat biodiesel were 3.6 BSU and 3.8 BSU, respectively, at full load. The 10% reduction in smoke emission for biodiesel with 15% DEE might be due to the presence of more oxygen in the DEE which made the combustion complete and also since the biodiesel fuel itself contained 11% oxygen in it which might promote the oxidation of soot during the combustion process [64]. Geo et

al declared that the smoke emission was 6.1 BSU (Bosch smoke units) with neat biodiesel and 3.4 BSU with diesel at full load as seen in Fig. 9(b). With neat biodiesel due to its heavier molecular structure and high viscosity, atomization became poor and led to higher smoke emission. There was a drastic reduction in smoke emission of the engine fuelled with DEE operation. Smoke decreased from 6.1 BSU to 4 BSU with DEE at a flow rate of 200 g/h at peak output. The volatility and oxygen enrichment provided by DEE was beneficial in improving the fuel evaporation and smoke reduction. Also high cetane number of the DEE resulted in shorter ignition delay. Shorter ignition delay reduced the accumulation of fuel in the combustion chamber and reduced the smoke emission. Thus, a small quantity of oxygenates injected with vegetable oil could be effective in reducing smoke emission [65].

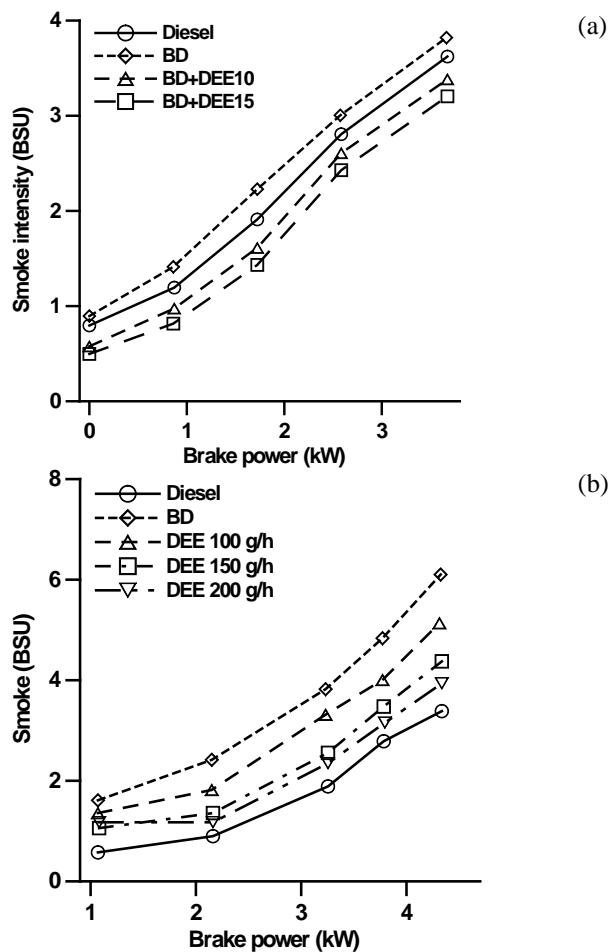
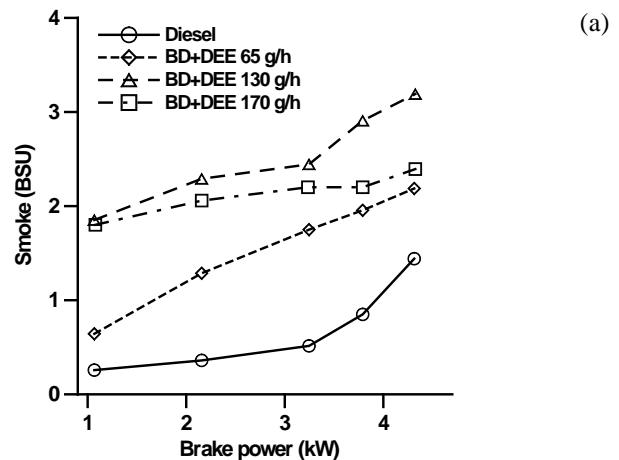


Figure 9. Effect of diethyl ether on smoke emissions of biodiesel fuel [64, 65]

Hariharan et al declared that smoke was due to the incomplete combustion of unsaturated hydrocarbons like polycyclic aromatic hydrocarbons that were present in the fuel. Smoke varied according to the type of fuel used, its composition, its carbon content and C/H ratio. It could be observed from Fig. 10(a) that smoke increased with increase in the induction of

DEE. For diesel operation, smoke emission varied from 0 at no load to 1.45 BSU at full load. It varied from 0.55 BSU at no load to 2.2 BSU at full load with biodiesel-DEE mode at 65 g/h of DEE induction, from 1.8 BSU at no load to 3.2 BSU at full load at 130 g/h and from 0.45 BSU at no load to 2.4 BSU at full load at 170 g/h. Smoke would be higher for fuels that have a value of hydrogen to carbon ratio lesser than 2. Current biodiesel had hydrogen to carbon ratio of 1.4. This was the main reason for a significant change in smoke emission for biodiesel-DEE operation than diesel fuel. Since biodiesel had higher aromatic content, the presence of unsaturated hydrocarbon like poly aromatic hydrocarbon resulted in higher smoke. Slow combustion of the biodiesel during the diffusion combustion phase and the pyrolysis of fuel at high temperature were also the reasons for higher smoke emission for biodiesel-DEE operation particularly at full load [66]. Devaraj et al declared that the smoke opacity of any fuel increased with the increase in load as seen in Fig. 10(b). The smoke opacity of biodiesel was higher than that of diesel due to heavier molecules. The smoke opacity level was 1.7% for 20% load and 53.5% at full load, in case of diesel. In case of biodiesel, the value was 2% at 20% load and 55.1% at full load. The smoke opacity for DEE5 and DEE10 at 20% load is 9.5% and 9.9% and at full load, it is 49.2% and 55.1%. The addition of DEE with biodiesel showed reduction in smoke opacity. This is due to the higher oxygen content of DEE depromoted the formation of smoke during the diffusion phase of combustion. The smoke opacity at high load obtained for DEE5 and DEE10 showed that there was an increment in smoke opacity. This indicated that beyond certain limit the addition of DEE had no effect in reduction of smoke opacity [67].

Sachuthananthan and Jeyachandran declared that smoke emission for 30% water-biodiesel emulsion was 2.5 BSU at full load and for 10% DEE it was 1.8 BSU and for 15% DEE it was 1.6 BSU as seen in Fig. 11(a).



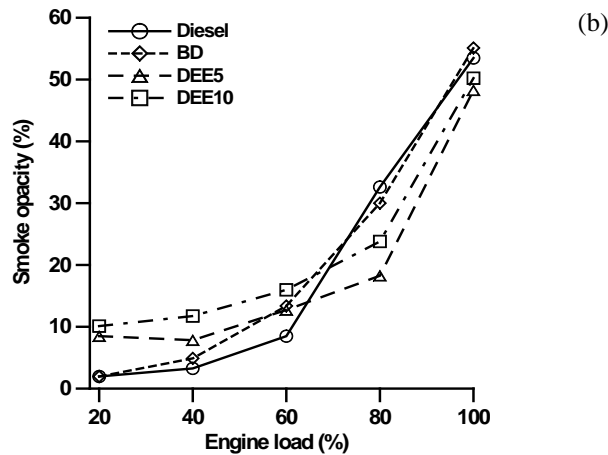


Figure 10. Effect of diethyl ether on smoke emissions of biodiesel fuel [66, 67]

This reduction in smoke emission for water-biodiesel emulsion with DEE was due to presence of 21.6% oxygen by mass in DEE which made the combustion complete and also since the biodiesel fuel itself contains 11% oxygen in it which might promoted the oxidation of soot during the combustion process [70]. Kumar et al declared that BD has prolonged aromatic chain-like structure and it has poor combustion. Thus, it results in more amounts of smoke level increases it may be due to poor atomization of the BD. It is observed that the smoke opacity of BD20 blend is higher than diesel. Result shows at full loading condition smoke level of BD20 is 3.96 FSN whereas for diesel its level is 3.15 FSN as seen in Fig. 11(b). After addition of DEE with BD20 it is reduced. It has been found that smoke level of BD20DEE15 is 3.38 FSN. This is because improved viscosity resulting improve combustion rate of the DEE blends [74].

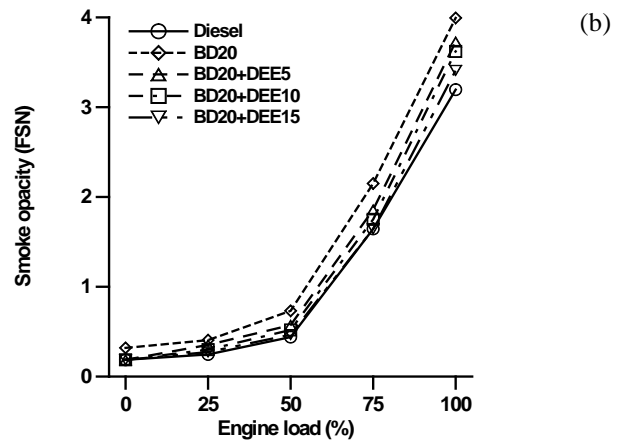
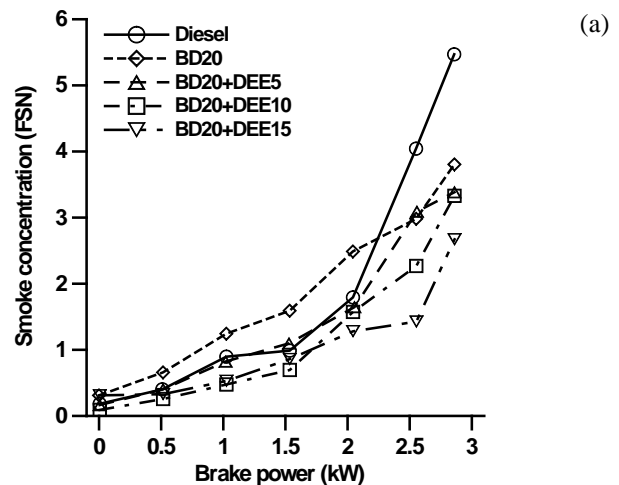
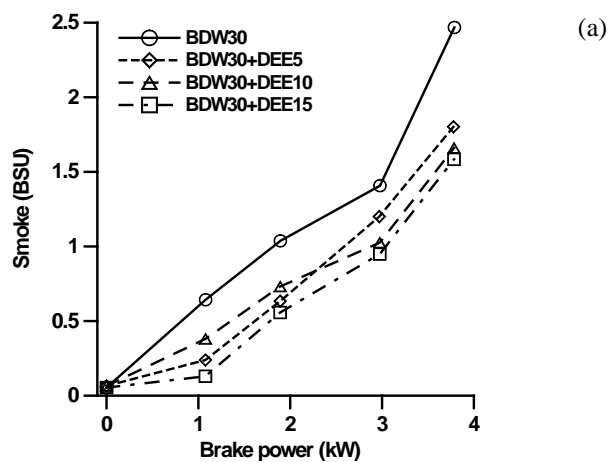


Figure 11. Effect of diethyl ether on smoke emissions of biodiesel-water emulsified fuel [70] and diesel-biodiesel blends [74]

Srihari et al declared that smoke level for all the blends are fairly lower than that of diesel as seen in Fig. 12(a). But, at low and medium loads smoke level seems to be almost the same for all the blends. Nevertheless, for DEE10 and DEE15 the smoke level is low for all the loads when compared to that of the others. Thus, DEE10 and DEE15 can be considered as better options as far as smoke concentration is concerned. Here, in the case of DEE15 a reduction in smoke concentration of 50% and 32% is observed when compared to that of diesel and BD20 at full load. The corresponding values for DEE10 are 30% and 38.5%. The reason for this reduction in smoke concentration can be attributed to the reduction in density due to the addition of DEE and the corresponding altered spray pattern leading to better fuel-air mixing process. Another reason could be the absence of fuel rich zone in the cylinder that leads to reduced smoke [76].



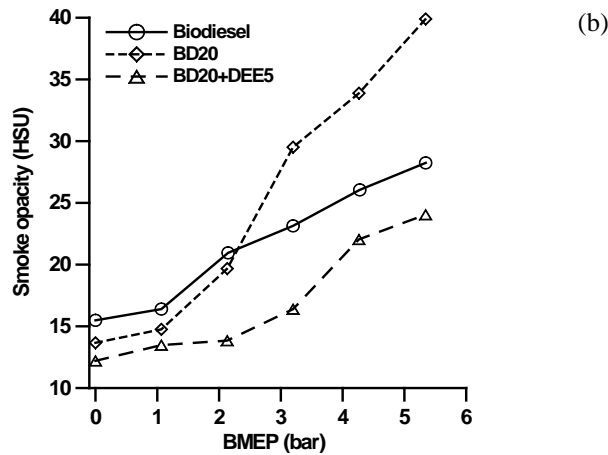


Figure 12. Effect of diethyl ether on smoke emissions of diesel-biodiesel blends [76, 81]

The smoke opacity exhibited by different fuels is plotted in Fig. 12(b). It can be seen that the values are on the lower side for the BD20 blend with DEE additive. Lowest values are observed for the case of BD20 with DEE5 and highest being BD. Improved and complete combustion could be the reasons for obtaining lower smoke opacity values with DEE additive. Therefore, it can be concluded here that DEE has proven to be eco-friendly additive to improve the performance and emissions of BD20 blend [81]. It is observed from Fig. 13(a) that the smoke emission is decreased with increase of DEE in BD20 blend at full load. The maximum smoke emissions for DEE10 and DEE15 are 3.4BSU and 3.2BSU, whereas they are 3.6BSU and 3.8BSU for diesel and BD20 blend respectively at full load. The 10% reduction in smoke emission for BD20 with DEE15 may be due to the presence of more oxygen in the DEE which makes the combustion complete and also since the biodiesel fuel itself contains 11% oxygen in it which may promote the oxidation of soot during the combustion process [83]. The smoke emissions variation is shown in Fig. 13(b). The smoke is formed due to incomplete combustion. It is obvious that the smoke emissions are reduced with DEE additive. This may be attributed to the engine running overall leaner with the combustion being now assisted by the presence of the fuel-bound oxygen of the diethyl ether even in locally rich zones. Additionally, diethyl ether has a remarkable effect on the reduction of smoke emissions due to it is evaporating easily, especially at high engine loads. So, DEE5 blend shows the lowest smoke emissions at all engine loads [85].

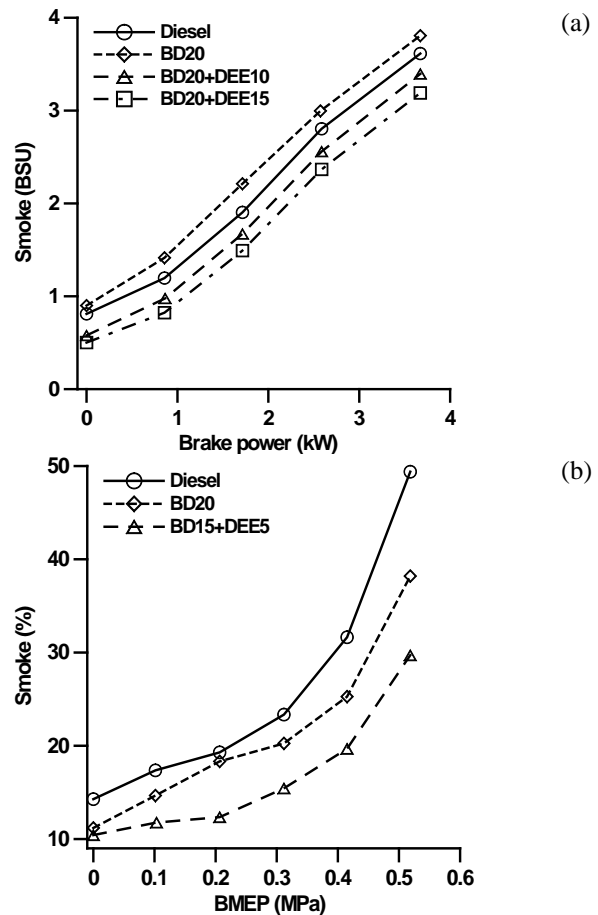


Figure 13. Effect of diethyl ether on smoke emissions of diesel-biodiesel blends [83, 85]

Smoke density of DEE5 is generally lower than that of BD20 and diesel as seen in Fig. 14(a). That is, lesser amount of unburned hydrocarbon presents in the engine exhaust gas. Thus, the lower smoke density values are achieved with DEE blends as compared to that of biodiesel and diesel [87]. Fig. 14(b) illustrates the smoke opacity of the test fuels. BD20 gave about 6.2% decreased smoke opacity than diesel fuel. It can be attributed to advanced start of combustion of BD20 for higher cetane number. Hence, the combustion started early, it allowed more time for the oxidation of soot. Soot formation takes place generally at the initial premixed combustion phase when the fuel-air equivalence ratio remains at stoichiometry. Therefore, higher oxygen content of BD20 provided oxygen in the fuel rich zones and reduced smoke opacity especially at higher speeds. BD15DEE5 and BD10DEE10 reduced smoke opacity about 30% and 38.5% on average than BD20. Therefore, it is obvious that such oxygenated blends reduced the probability of rich fuel zone formation and assisted to decrease the soot emission [91].

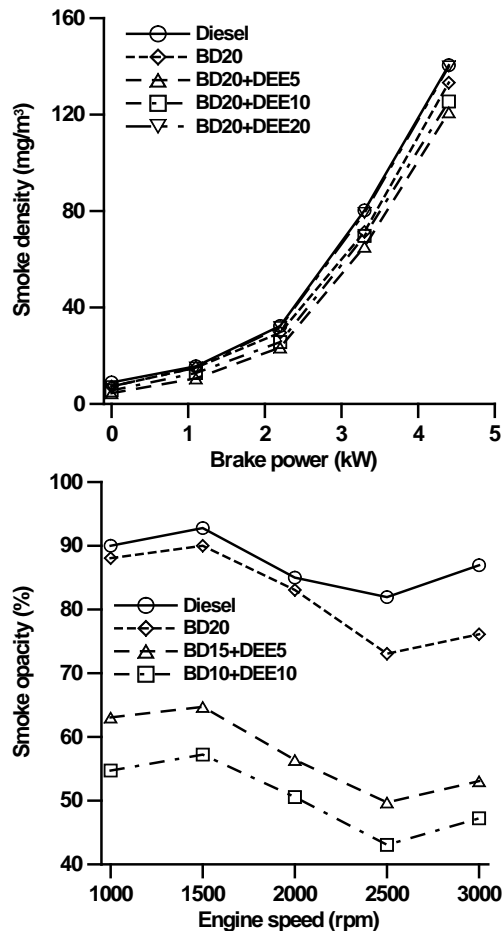


Figure 14. Effect of diethyl ether on smoke emissions of diesel-biodiesel blends [87, 91]

Smoke emission in diesel engines occurs due to the incomplete combustion inside the combustion chamber and is normally formed in the rich zone. The variation of smoke emission, with brake power for diesel, BD40 and DEE4 blends are depicted in Fig. 15(a). The smoke emission increases with increasing load. This is due to the increase in the mass of fuel consumed when brake power is increased. The smoke emission for BD40 blend is the highest at full load. The smoke emission reduces with adding of DEE to BD40 blend. The volatility and oxygen enrichment provided by DEE is beneficial to improving the fuel evaporation and smoke reduction. The smoke emissions of DEE4 are approximately 21% lower compared to that of diesel, and about 34% lower compared to that of the BD40 blend at full load [107].

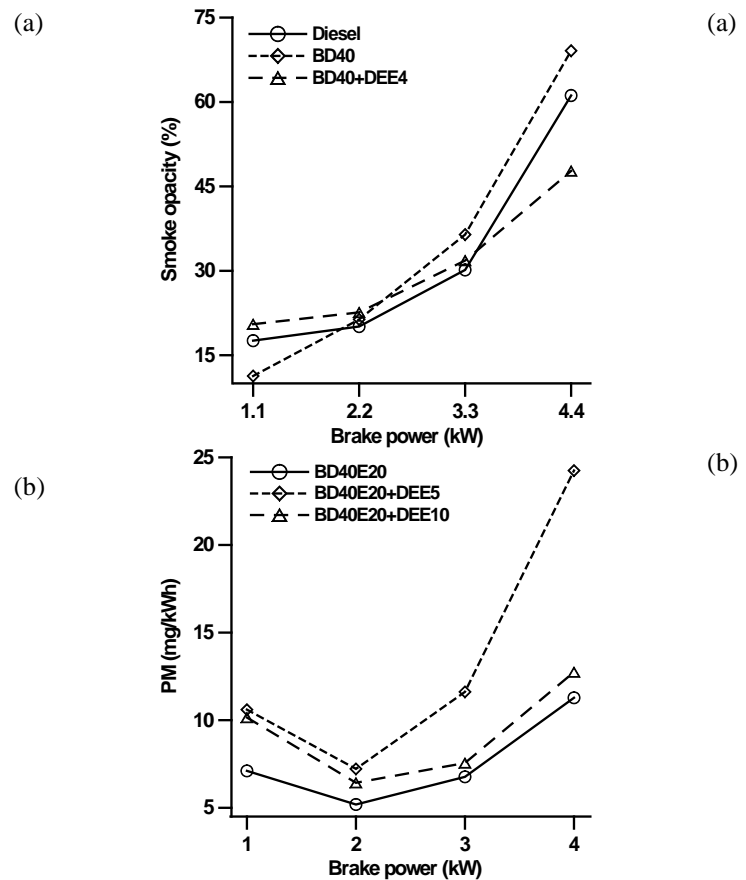


Figure 15. Effect of diethyl ether on smoke emissions of diesel-biodiesel blends [107] and PM emissions biodiesel-ethanol blends [110]

Particulate matter (PM) is generated as a result of insufficient O₂ content in fuel rich zones, especially during heterogeneous combustion. In general, in comparison with diesel, oxygenate blends lowers the PM emissions due to reduced aromatics, C/H ratio and the presence of readily available O₂, which improves the combustion rate followed by lower PM formation. From Fig. 15(b), DEE10 blend has highest PM in comparison with other fuels. At lower loads, PM formation is less owing to less fuel fraction burnt, whereas PM formation increases with increasing load due to excess fuel accumulation resulting in higher burn duration. At all engine loads, the presence of DEE additive has raised the PM emission in comparison with BD40E20 blend [110].

5. Conclusion

The effect of diethyl ether addition to various diesel engine fuels and fuel blends is investigated on the PM and smoke emissions in this review study. The following conclusions can be summarized as results of the study.

- Smoke, soot or particulate matter is direct indication of incomplete combustion in the engine and these are formed in fuel rich regions in the combustion chamber.

- Smoke emissions increase with increasing engine speed and load due to short combustion duration, long delay period and shortage of oxygen as the amount of fuel injected increased.
- DEE addition various diesel engine fuels reduces the PM and smoke emissions by enabling better mixing of air-fuel mixture and providing more complete combustion due to high cetane number and oxygen content of DEE. The improvement in spray atomization and fuel-air mixing with the addition of diethyl ether decreased the rich mixture region and decreased the smoke emission. High volatility of DEE also has a remarkable effect on the reduction of smoke emissions. Moreover, DEE has positive effect on the elimination of soot formation because of the low carbon to hydrogen ratio.
- In some studies, the increase of DEE in the blend increases the smoke emissions due to the phase separation of the blend. This shows that DEE addition beyond certain limit has no effect in reduction of smoke opacity. On the other hand, the increasing of hot EGR causes the increasing of smoke emissions than in the case of without EGR.
- The neat biodiesel fuels generate the higher smoke emissions by causing poor atomization due to its heavier molecular structure, high viscosity and the presence of unsaturated hydrocarbons. However, important improvements achieve with biodiesel-diesel blends and DEE addition in smoke emission.

ABBREVIATIONS

BD	: Biodiesel
BD-D	: Biodiesel-diesel blends
BSU	: Bosch smoke units
C/H	: Carbon to hydrogen ratio
CNSO	: Cashew nut shell oil
D	: Diesel
D-BD-DEE	: Diesel-biodiesel-diethyl ether blends
DBE	: Dibutyl ether
DEE	: Diethyl ether
DGM	: Diethylene glycol dimethyl ether
DMC	: Dimethyl carbonate
DME	: Dimethyl ether
DMM	: Dimethoxy methane
E	: Ethanol
EGR	: Exhaust gas recirculation
FSN	: Filter smoke number
HCCI	: Homogenous charge compression ignition
K	: Kerosene
kW	: Kilowatt
MTBE	: Methyl tertiary butyl ether
NG	: Natural gas
PAHs	: Polycyclic aromatic hydrocarbons
PCCI	: Partially charge compression ignition
PM	: Particulate matter
ppm	: Parts per million
SO _x	: Sulphur oxides
THC	: Total gaseous hydrocarbons

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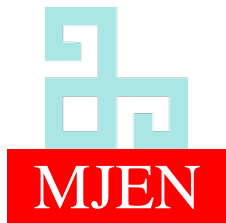
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