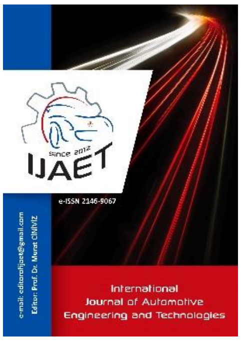
e-ISSN: 2146 - 9067

International Journal of Automotive Engineering and Technologies

journal homepage: http://ijaet.academicpaper.org



Original Research Article

A Review Study on the Using of Diethyl Ether in Diesel Engines: Effects on NOx Emissions

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ARTICLE INFO

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Received: October 26, 2018
Accepted: December 19, 2018

Published by Editorial Board Members of IJAET

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 have used the reduction of the harmful exhaust emissions of diesel engines. The first technique for the reduction of harmful emissions has 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 improve diesel engine performance is the use of various alternative fuels or fuel additives. The major pollutants of diesel engines are an oxide of nitrogen (NOx) and smoke or particulate matter (PM). It is very difficult to reduce NOx and PM simultaneously in practice. The most researches declare that the best way to reduce is the use of various alternative fuels i.e. natural gas, biogas, biodiesel or using 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 practical applications. Especially, this study focuses 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 NOx emissions.

Keywords: Diesel engine performance, NOx emissions, Fuel additives, Diethyl ether

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 suffer from their high emission drawbacks like particulate matters (PM), total gaseous hydrocarbons (THC), nitrogen oxides (NOx), sulphur oxides (SOx) and smoke [3, 4]. It is seeming that the most suitable way to reduce of these emissions is the using of alternative fuels made from renewable sources instead of commercial fuels [5]. However, complete replacement of fossil fuels with renewable alternative fuels will require 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 [7-9]. 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, NOx 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 because it is a cetane improver besides an oxygenated fuel [13]. Therefore, this review study is devoted to the 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 CH3CH2-O-CH2CH3, consisting of two ethyl groups bonded to a central oxygen atom as seen in Fig. 1.

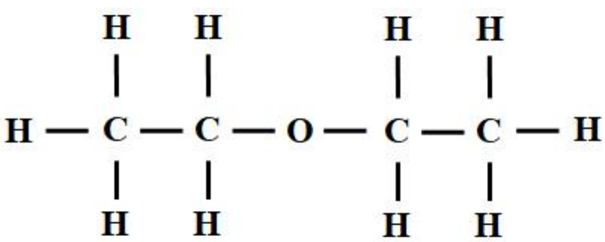


Fig. 1. Diethyl ether chemical composition [3]

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].

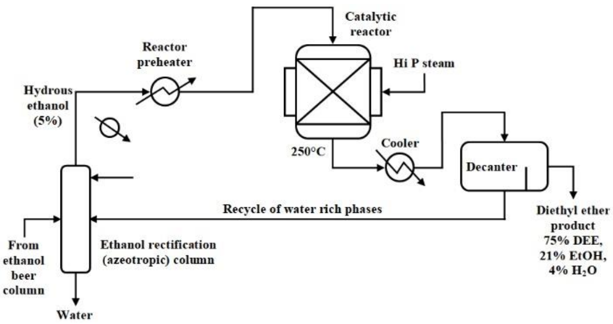


Fig. 2. Production of diethyl ether from ethanol [14]

As shown in Table 1, DEE has several favorable properties, including exceptional cetane number, reasonable energy density, high oxygen content, low auto ignition temperature and high volatility. Therefore, it can be assisting in improving 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	$C_4H_{10}O$
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
Sulphur content (ppm)	~250	-
Boiling temperature (°C)	180-360	34.6
Auto ignition temperature in air, °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 those of many fuels, but the rich flammability limit of DEE is in question [14].

3. Studies on Diethyl Ether in Literature

There are several studies in the literature on the use of DEE in diesel engines as a fuel or fuel additive in various diesel engine fuels. For example; as pure [16], with diesel fuel [17-32], with diesel-ethanol blends [33-40], with diesel-ferric chloride blends [41], with diesel-kerosene blends [42], with diesel-acetylene gas dual fuel [43], with biogas [44], with liquefied petroleum gas [45], with diesel-natural gas dual fuel [46], with ethanol [47, 48], with various biodiesel fuels [49-68], with biogas-biodiesel blends [69], with water-biodiesel emulsion fuel [70], with various biodiesel-diesel blends [71-109], with ethanol-biodiesel-diesel blends [110-113] and methanol-biodiesel-diesel blends [113].

4. Effects of Diethyl Ether on NOx Emissions

Sezer [15] declared that NO emission became higher for equal equivalence ratio condition, while it was lower for equal mass fuel injection condition for DEE. The reduction in NO emission was achieved by lower combustion temperatures. However, increases in NO emission for equal equivalence ratio condition could be attributed to rises in combustion temperatures of DEE and abundant oxygen sourced from the increased mass of DEE. The higher combustion temperature led to dissociation reactions and abundant oxygen in the combustion chamber contributed dissociation products such as NO. Rakopoulos et al [17] declared that NOx emitted by all DEE-diesel blends were lower than diesel fuel as seen in Fig. 3(a). The reduction is higher for higher the percentage of DEE in the blend. This might be attributed to the engine running overall leaner and the temperature lowering effect of the DEE having the dominating influence, partially outweighed by the extra fuel-bound oxygen bringing more ‘zones’ near to stoichiometric conditions and little to the lean, where NOx was highly formed. Banapurmath et al [22] declared that the formation rate of NOx is primarily a function of flame temperature, the residence time of nitrogen at that temperature and the availability of oxygen in the combustion chamber. NOx emission was increased with the engine load as seen in Fig. 3(b). This was due to the increased quantity of fuel is injected and combusted in the cylinder when engine load increased, which caused higher gas temperature and resulted in more NOx formation. It also can be seen that NOx emission was slightly reduced with DEE blends compared to diesel fuel. This was due to low combustion temperature because of low calorific value and the high latent heat of vaporization of DEE resulted in reduced flame temperature and lower NOx emissions.

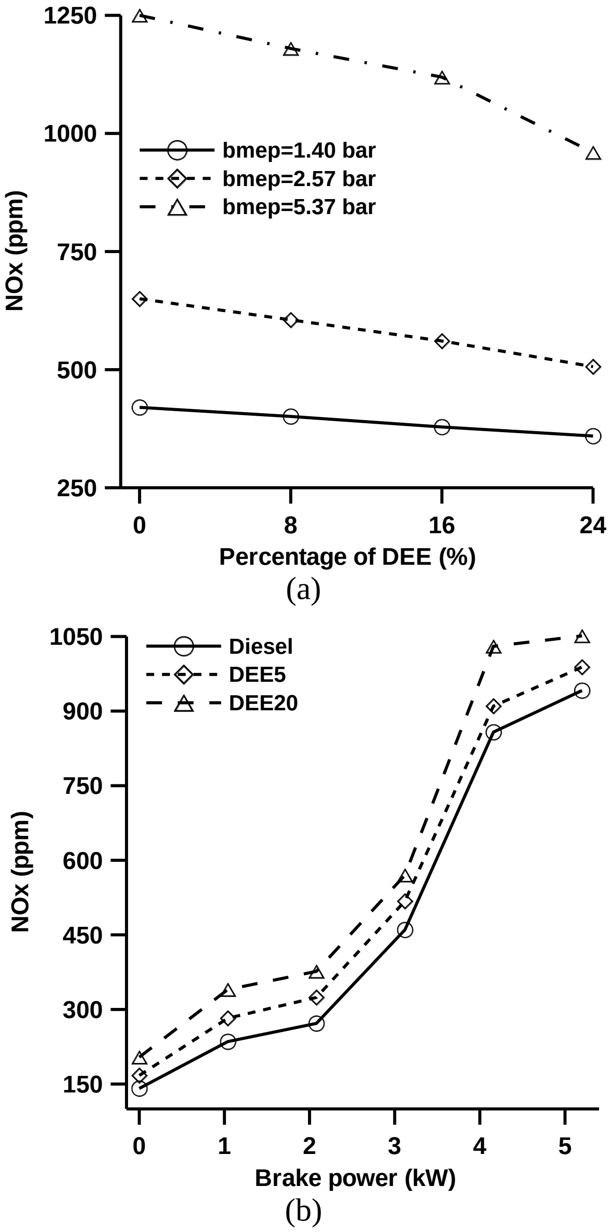
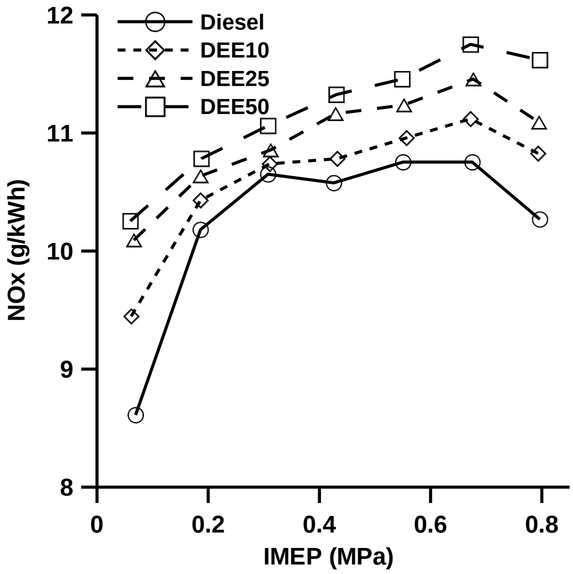


Fig. 3. Effect of diethyl ether additive on NOx emissions of the diesel fuel [17, 22]

Lee and Kim [23] declared that NOx was the lowest at a low engine load because excess air cooled down the mixture, resulting in low NO_x emissions. NOx emissions for diesel were lower than DEE blends and increased with increasing in DEE content as seen in Fig. 4(a). Formation of NOx emissions was strongly dependent on the cylinder peak temperature and local oxygen concentration. The oxygen content of DEE brought more zones near to stoichiometric conditions and little to the lean, and these conditions favor for NOx formation. Additional oxygen availability resulted in the more complete combustion of the fuel-air mixture and increased the burned gas, which tended to be converted into more NOx in the high-temperature regions during combustion. One more possible explanation for the higher NOx emissions of the blended fuels was the shorter ignition delay due to the addition of DEE.



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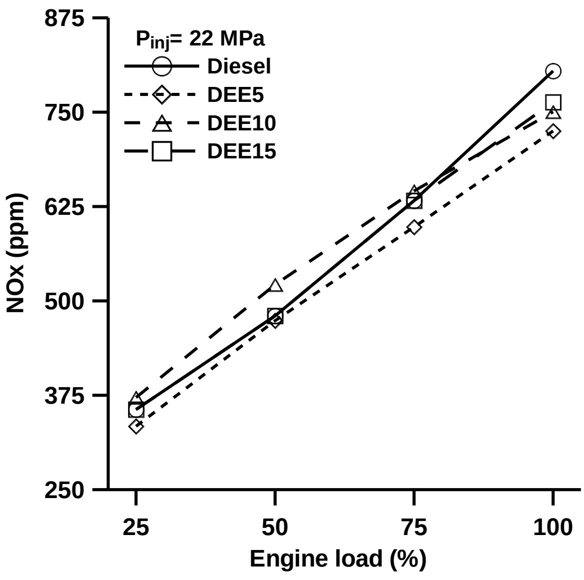


(b)

Fig. 4. Effect of diethyl ether additive on NOx emissions of the diesel fuel [23, 29]

Saravanan et al [24] declared that NOx emissions slightly decreased with DEE addition. The reduction in the peak combustion temperature due to the addition of DEE which reduced the calorific value of the blend helped in reducing the NOx emissions. The reduced ignition delay period and shortened combustion duration due to higher cetane number of DEE also helped in reducing the NOx emission. Madhu et al [29] declared that NOx emission was reduced with blending DEE to diesel as seen in Fig. 4 (b). At a given injection pressure, as the composition of DEE increased, NOx also increased. However, as the injection pressure and composition of DEE increased, NOx emission was found to be decreasing. There was 9% reduction in NOx with E5D95 at 22MPa injection pressure. This was due to the diminishing fuel particle size at higher pressures and enhanced mixing of fuel with air. Higher injection pressure generated faster combustion rates and as the premixed combustion was shortened, the peak cylinder temperature reduced with the addition of DEE.

Prasadarao et al [31] declared all the blends tested produced higher NOx emission than diesel fuel except for BD15DEE5, while biodiesel fuel had lower NOx emissions than diesel fuel at higher loads as seen in Fig. 5(a). As cetane number of biodiesel fuel was higher than diesel, it exhibited a shorter delay period and resulted in better combustion leading to low NO emissions but when it was blended with DEE produced more NO emission. On the other hand, the remarkable reduction was obtained with BD15DEE5.

Cinar et al [32] declared that NOx emissions were reduced with increase in the premixed DEE fuel ratio. NOx emissions were mostly generated by thermal mechanisms during the diffusion combustion stage. Most of the heat release rate occurred during the premixed combustion phase and the diffusion combustion phase decreased with the increasing premixed ratio of DEE. Therefore, the main combustion occurred after TDC and thus resulted in lower NO_x emissions caused by cylinder temperatures. NOx emissions were decreased by 19.4% under HCCI-DI operating conditions as seen in Fig. 5(b). Iranmanesh [33] declared that as the quantity of DEE in the blends increased, dynamic injection timing was altered due to problems encountered with the fuel pump and lowering the density, viscosity and bulk modulus of the blends which led to late injection and consequently ignition retard. Then, the start of combustion and heat release was postponed. Moreover, due to the high latent heat of DEE, the peak pressure and peak heat release rate were suppressed, hence as a result of these two factors NOx emissions drastically reduced as seen in Fig. 6(a). Ethanol and DEE blending into diesel fuel reduced temperature both by increased heat of vaporization and reduced flame temperature. Consequently, combustion temperature abated, and hence NOx emissions were diminished. The blend of E10DEE8 had the lowest NOx emissions such that 36.6% and 43% improvement was observed at full load condition in compare with E10 blend and diesel fuel respectively.

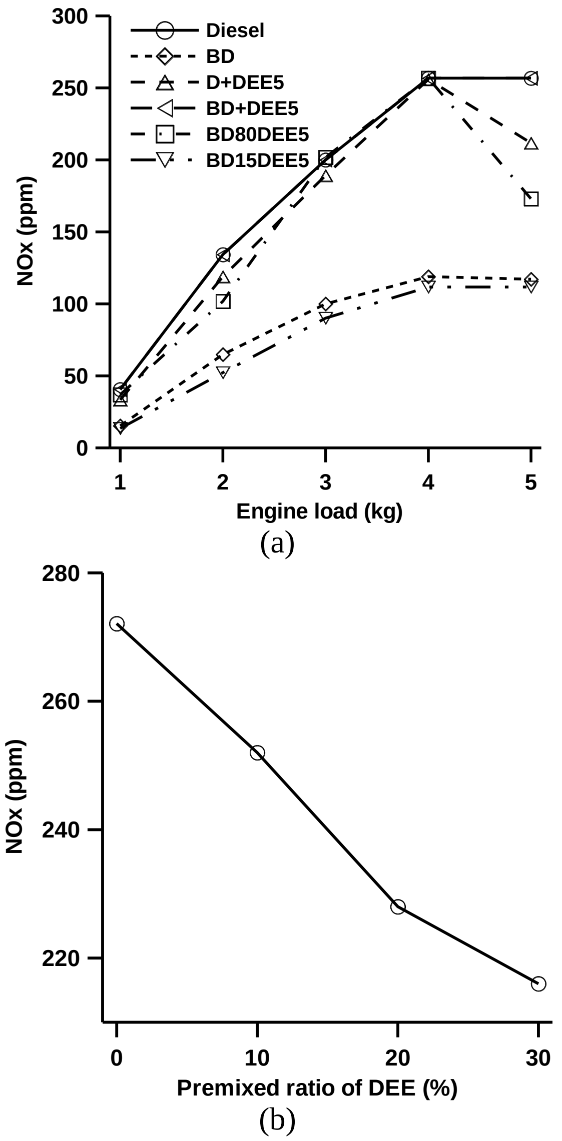


Fig. 5. Effect of diethyl ether additive on NOx emissions of biodiesel-diesel blend [31, 32]

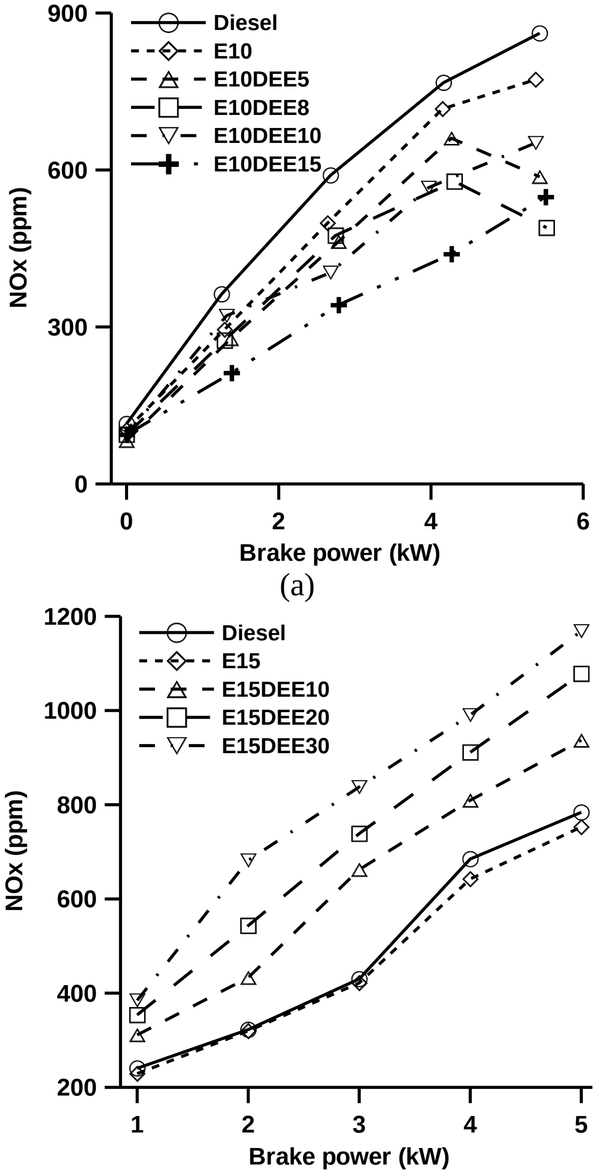
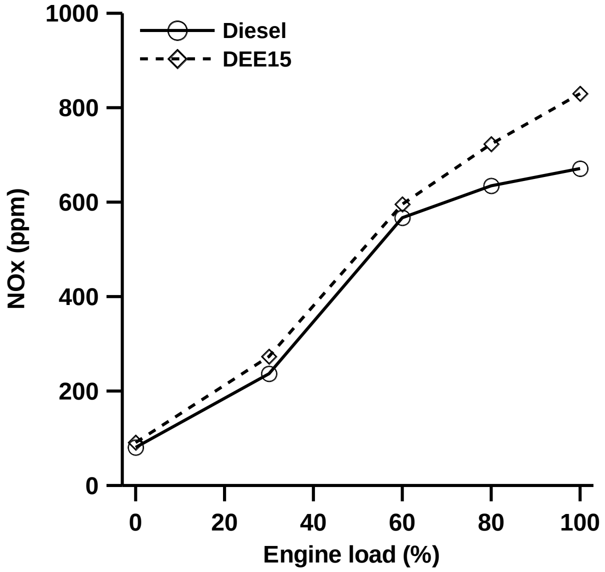


Fig. 6. Effect of diethyl ether additive on NOx emissions of ethanol-diesel blends [33, 35]

Sudhakar and Sivaprakasam [35] declared that ethanol blended diesel E15 showed a slight decrease in NOx, when the injection percentages of DEE increased the NOx emissions were increasing drastically as seen in Fig. 6(b). This was mainly due to oxygen available in DEE increased the cylinder temperature while combustion took place that led to the formation of oxides of nitrogen and that was evidently proved in heat release rate and exhaust temperature of the test engine. The highest 48% increase in NOx emission was recorded at 30% of DEE injection while comparing with diesel fuel. Sudhakar and Sivaprakasam [36] declared that the fumigation of DEE in large quantity increased NOx emission by 49%. The increasing percentage of DEE injection marginally increased the NOx emission. However, the EGR revealed good control over the NOx emission reduction. Paul et al [37] declared that NOx emission decreased with DEE5 blend at low load but increased with medium and high load conditions. At lower load conditions, the energy requirement of the engine was relatively lower. Because of this, less amount of fuel was injected and burned in the combustion chamber, producing a lower cylinder temperature. Since NOx formation was prominently dependent on high cylinder temperature, so NOx emission reduced at low loads. However, at the higher load conditions, a higher amount of fuel was injected and burned, producing higher cylinder temperature. DEE10 blend also followed the same trend of low NOx emission at low load and increased NOx emission at high load conditions. However, it was seen that NOx emission for DEE10 was significantly lower than DEE5. It might be due to the reduced ignition delay that reduced the fuel-air mixing time and deteriorated the combustion condition. This reduced combustion of the charge produced lower cylinder heat generation that resulted in lower NOx emission. NOx emission was significantly reduced with the ethanol addition to the diesel-DEE blends. DEE5E5 blend reduced the NOx emission by 14.28% at full load condition as compared to baseline diesel. This reduction in NOx emission might be attributed to the cooling effect of ethanol. This effect was more prominent for DEE5E10 blend, where it produced a maximum reduction of 20.76% at medium load condition. For DEE10E5 and DEE10E10 blends, a prominent reduction in NOx emission was also observed. DEE10E5 blend produced a maximum decrease of 25.95%, whereas DEE10E10 blend produced a reduction of 27.58%. Patnaik et al [41] declared that NO emission increased for DEE15 blend by 35% than that of diesel fuel at full load as seen in Fig. 7(a). Due to low boiling point and presence of molecular oxygen in DEE the mixture improved combustion and higher cetane value of DEE advanced the combustion leading to early-stage combustion during the premixed stage where NO was formed mostly. Karabektas [46] declared that the use of natural gas as a dual fuel (NG40) yielded a decrease in the NO emissions at low and medium loads but an increase at high loads in comparison to diesel fuel. The NO emissions decreased with the use of DEE compared with NG40.



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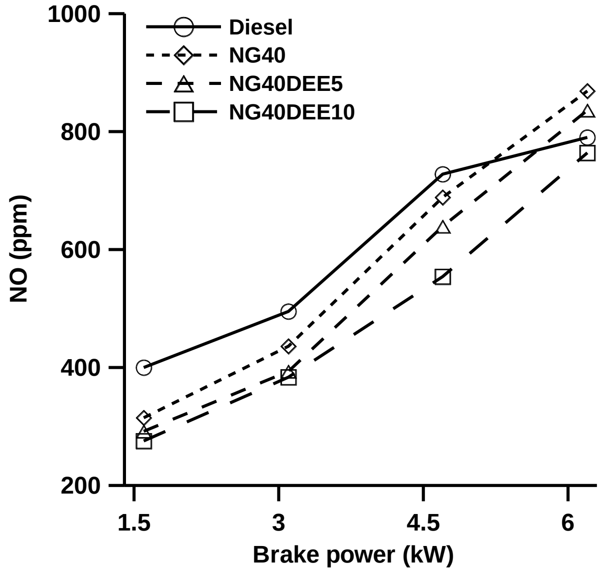


(b)

Fig. 7. Effect of diethyl ether additive on NOx emissions of diesel [41] and natural gas-diesel dual fuel [46]

Furthermore, the higher the DEE content resulted in the lower NO emissions as seen in Fig. 7(b). The decrease in NO emissions obtained with the DEE blends compared with NG40 might originate from various reasons. Because DEE had a considerably high cetane number, oxygen content and high heat of evaporation, it was easy to ignite the fuel-air mixture, and it yielded a shorter combustion duration. By adding DEE, heat release decreased in the stage of diffusion-controlled combustion, thereby leading to lower NO emissions. Moreover, DEE blends with oxygen content showed that the NO emissions decreased due to the lower high-temperature duration that the combustion gases experienced. Furthermore, the high cetane number of DEE caused lower NOx emissions particularly at medium-high loads and decreased ignition time and maximum rate of heat release. Another factor which caused lower NO emissions is the high heat of evaporation of DEE.

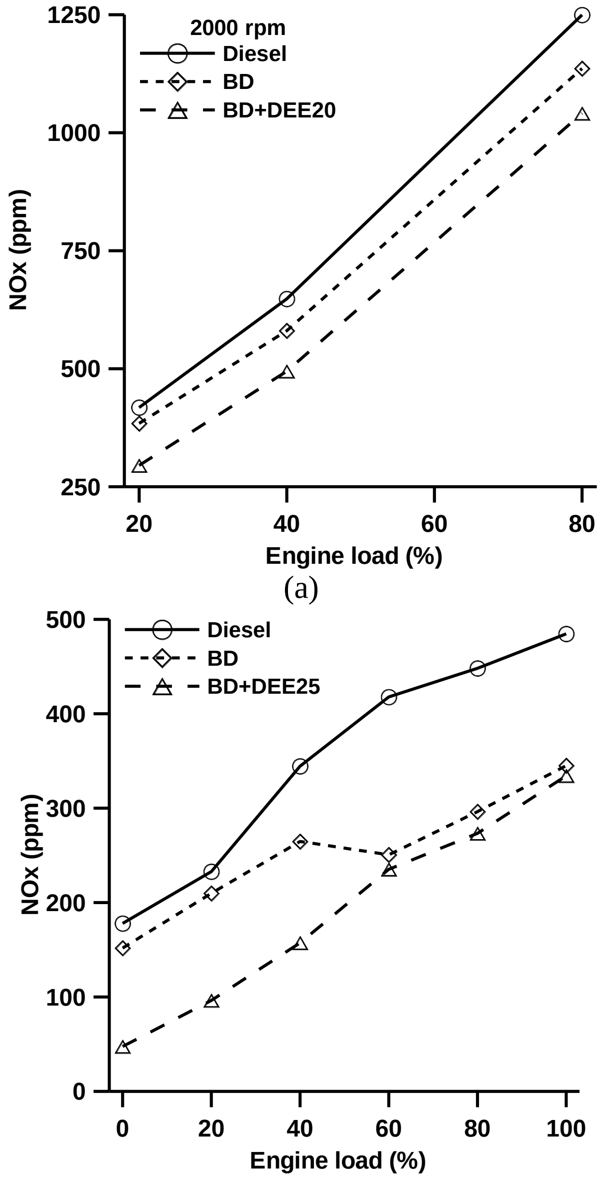


Fig. 8. Effect of diethyl ether additive on NOx emissions of biodiesel [50, 53]

Rakopoulos [50] declared that NOx emitted by the DEE blends were lower than those of the neat biodiesel and diesel as seen Fig. 8(a). This might be attributed to the relatively reduced premixed part of combustion where NOx was mainly formed and the associated lower cylinder temperatures. Krishna [53] et al declared that NOx emissions were significantly lower for the DEE blends at lower loads, whereas the gap slightly narrowed down at higher load conditions as seen in Fig. 8(b). The important factors for NOx formation were the peak combustion temperature in cylinder and availability of O_2 in the combustion chamber. NOx of 25% DEE blends with Karanja oil operation was 265 ppm as compared to 347 ppm of pure Karanja oil and 488 ppm of pure diesel operation respectively.

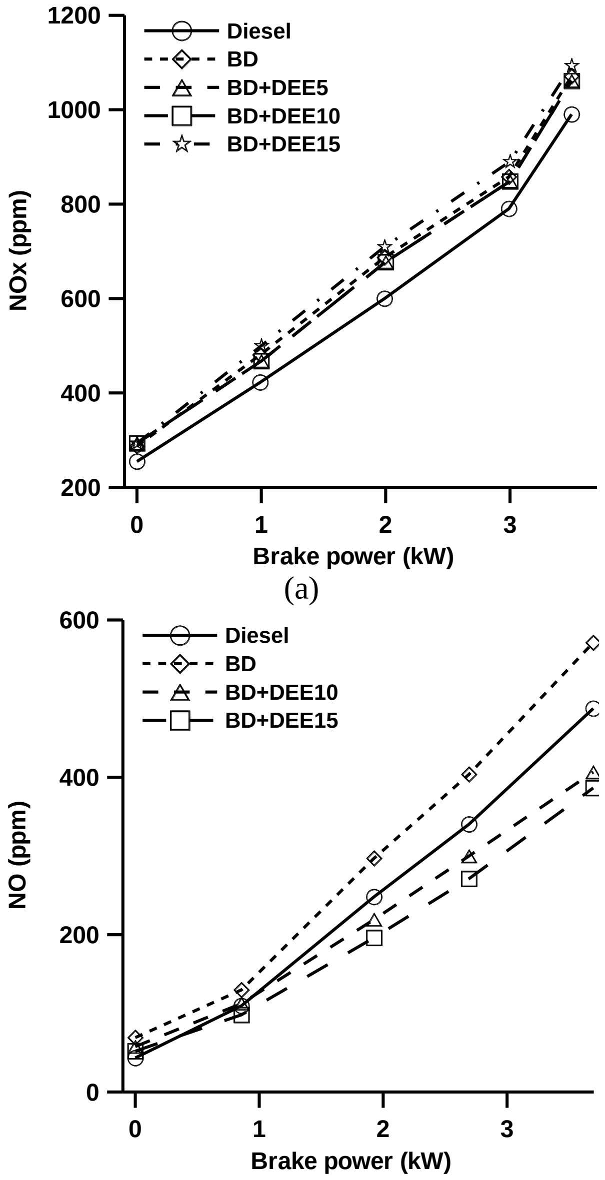


Fig. 9. Effect of diethyl ether additive on NOx emissions of biodiesel [59, 64]

Sivalakshmi and Balusamy [59] declared that NOx emissions are sensitive to oxygen content, adiabatic flame temperature and spray characteristics. NO_x emission increased with the use of DEE5 as seen in Fig 9(a). This might be due to the more complete combustion which resulted in a higher combustion temperature, leading to higher NOx emissions. NOx emission was lower with DEE10 blend as compared to DEE5. This might be due to a reduction in ignition delay. However, in the case of DEE15 blend, the NOx emission increased. This might be due to higher peak cylinder pressure and heat release rate, which was produced under some erratic conditions, leading to increased NOx emissions.

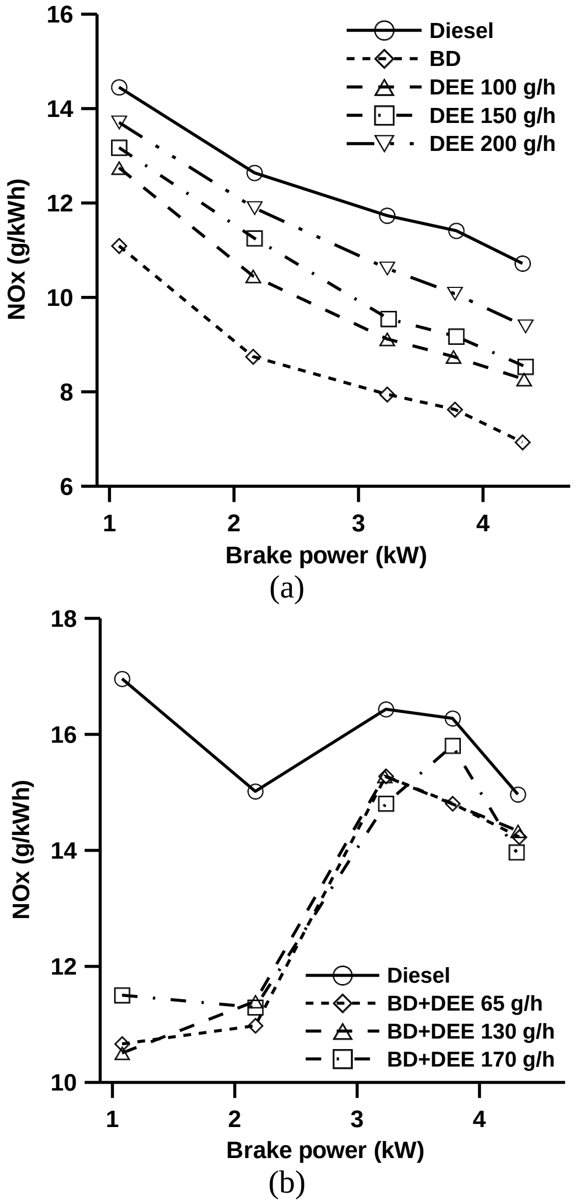


Fig. 10. Effect of diethyl ether additive on NOx emissions of biodiesel [65, 66]

Rajan et al [64] declared that NO emission increased for neat biodiesel and it decreased with the increase of DEE in the blends with neat biodiesel at full load as seen in Fig. 9(b). The maximum NO emissions for 10% and 15% DEE are 410 and 385 ppm, whereas the same for diesel and neat biodiesel were 486 and 568 ppm, respectively at full load. The NO emission decreased by 32% for 15% DEE and 26% for 10% DEE at full load compared with neat biodiesel. The decrease in NO emission for DEE might be due to the high latent heat of vaporization of DEE, resulting in cooling the charge at full load compared with biodiesel. Geo et al [65] declared that neat biodiesel showed lower NOx emissions as compared to diesel as seen in Fig. 10(a). The maximum NOx emission was 10.7 g/kWh with diesel and 6.9 g/kWh with biodiesel at maximum output. Due to poor combustion of the injected fuel during premixed combustion with biodiesel was lower and resulted in lower NOx emissions. But DEE admission with biodiesel increased the NOx emission. The maximum NOx emission was 9.3 g/kWh with biodiesel-DEE at the optimum quantity of 200 g/h. The addition of DEE with biodiesel caused a high temperature, promoted by higher premixed combustion and oxygen enrichment. This was due to the high combustion temperature caused by the early combustion of DEE. The combustion temperature had a strong effect on the production of NOx and therefore if the combustion temperature was higher, the NOx emission would also be higher.

Hariharan et al [66] declared that for diesel operation, NOx varied from 16.9 g/kWh at low load to 14.9 g/kWh at full load, from 10.7 g/kWh at low load to 14.3 g/kWh at full load for DEE at 65 g/h, from 10.4 g/kWh at low load to 14.2 g/kWh at full load for 130 g/h as seen Fig. 10(b). At 170 g/h, NOx varies from 11.5 g/kWh at low load to 13.9 g/kWh at full load. From the figure, it can be seen that while running on biodiesel with DEE at different flow rates, the NOx value decreased significantly with increase in the flow rate of DEE at low loads. This was due to the induction of a higher quantity of DEE at low load. The latent heat of DEE cooled the intake charge and reduced the peak flame temperature and hence NOx was lower than diesel. At full load, the amount of DEE inducted was less compared to low load and this was the reason for higher NOx formation. NOx values for biodiesel with DEE at 130 g/h and 170 g/h are lesser compared to biodiesel with DEE at 65 g/h. This might be attributed to a reduction in ignition delay.

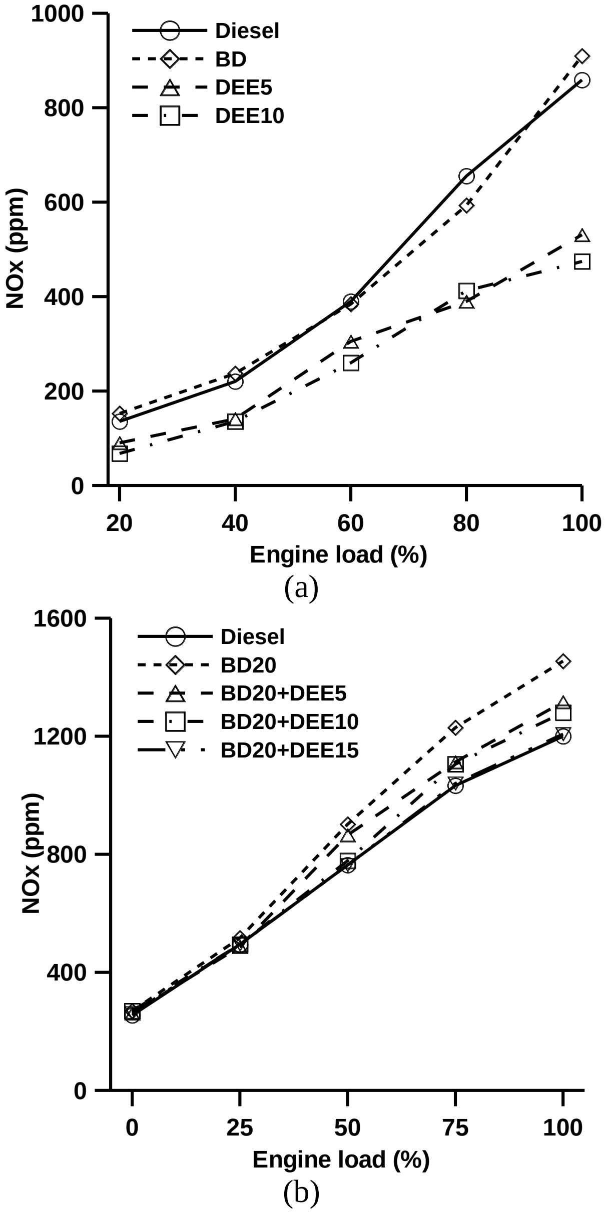
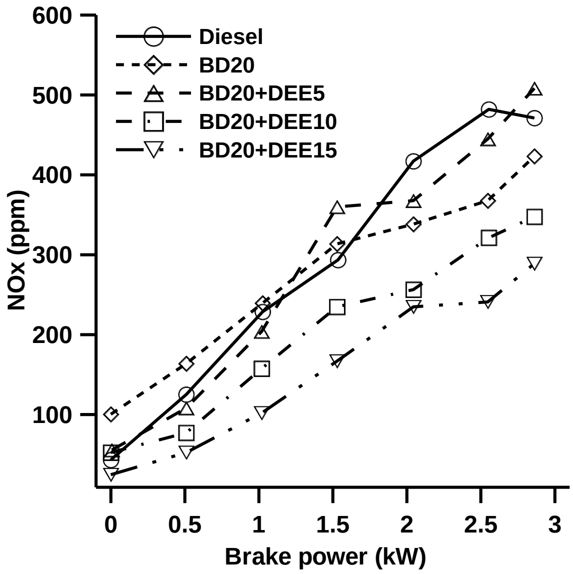


Fig. 11. Effect of diethyl ether additive on NOx emissions of biodiesel [67] and diesel-biodiesel blends [74]

Devaraj et al [67] declared that NOx values for diesel varied from 129 ppm at 20% load and 855 ppm at full load as seen in Fig. 11(a). For biodiesel, it varied from 150 ppm at 20% load and 904 ppm at full load. For DEE5 and DEE10, it varied from 91 to 71 ppm at 20% load and 529 ppm and 473 ppm at full load. The NOx formed was increasing as the load increased. The NOx emissions of the blends were found to reduce with increasing blend percentage of DEE with biodiesel. Since DEE was a cetane improver and an increase in cetane number decreased NOx emission. DEE has high oxygen content and high heat of evaporation. It was easy to ignite the fuel-air mixture and it yielded shorter combustion duration. By the addition of DEE, heat release decreased in the stage of diffusion-controlled combustion, thereby leading to lower NOx emissions. Another factor which caused lower NOx emissions was high heat of evaporation of DEE. Because DEE had a considerably high cetane number, oxygen content and high heat of evaporation, it was easy to ignite the fuel-air mixture, and it yielded shorter combustion duration. By adding DEE, heat release decreased in the stage of diffusion controlled combustion, thereby leading to lower NO emissions. Kumar et al [74] declared that NOx emissions of Cashew nut shell oil (CNSO)-diesel blend (CDB) are higher than that of diesel fuel as there is a reduction in HRR and combustion temperature. This will result in high NOx concentration in the exhaust. It is observed that NOx for diesel fuel is 1195 ppm and BD20 blend is 1450 ppm as seen in Fig. 11(b). After addition of DEE, NOx for BD20 is 1450 ppm which is higher than that of BD20DEE5 (1327ppm). It means that the addition of DEE in BD20 blends reduces the NOx emission. Srihari et al [76] declared that NOx levels for diesel and BD20 blend are considerably higher than the NOx levels for DEE10 and DEE15 irrespective of the load conditions as seen in Fig. 12(a). However, the DEE5 blend does not show any visible reduction in NOx emissions. The low NOx level of DEE10 and DEE15 could be mainly due to a reduction in combustion temperature with the addition of DEE. It is also seen that the increase in the percentage of DEE significantly decreases the NOx emissions. The main reason for this phenomenon is mainly due to the increase in latent heat of vaporization of the blends with the increasing percentage of DEE. Another reason could be the higher cetane number achieved with the addition of DEE which improves the combustion quality. It is seen that an average reduction of 29.6% and 22.3% are achieved for DEE10 blend when compared to BD20 and diesel respectively. The corresponding reductions in NOx level for the DEE15 blend are seen to be 42% and 46%.

Abraham and Thomas [79] declared that NOx emission increases with brake power for all the fuels as seen in Fig. 12(b). Since the formation of NOx is very sensitive to temperature, these higher loads promote cylinder charge temperature, which is responsible for thermal NOx formation. The biodiesel and DEE additives reduce the mean temperature inside the combustion chamber thereby reducing NOx emission.



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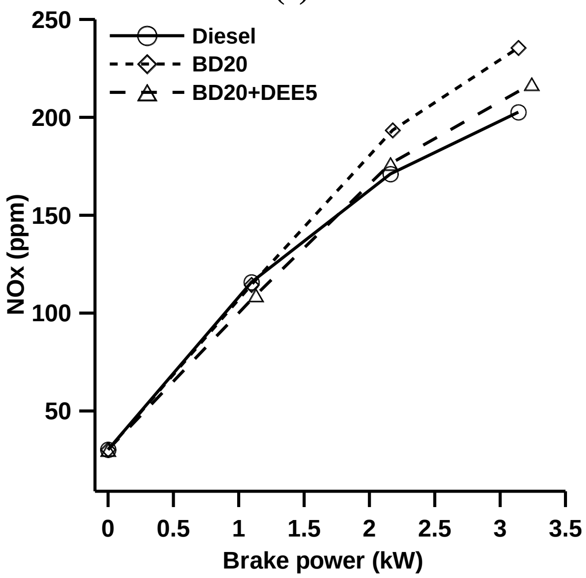

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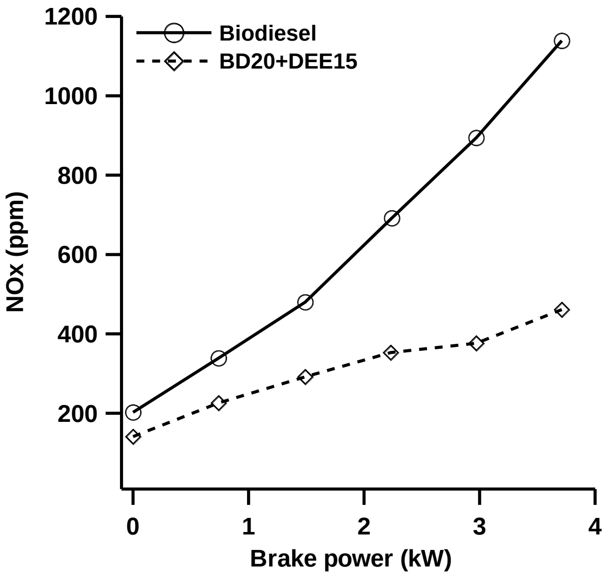
Fig. 12. Effect of diethyl ether additive on NOx emissions of diesel-biodiesel blends [76, 79]

It is clear from Fig. 13(a) that addition of higher proportions of DEE could reduce NOx levels with the BD20 blend. This may be attributed to the fact that higher quantities of DEE associated with its latent heat of vaporization could bring down the peak cycle temperatures. Prevalence of lower peak cycle temperatures is the reasons for not favoring the thermal prompt reactions responsible for the formation of higher levels of NOx [81]. It is observed from Fig. 13(b) that the NO emission was increased for BD20 and it is decreased with the increase of DEE in BD20 blend at full load. The maximum NO emissions for DEE10 and DEE15 are 410ppm and 385ppm, whereas for diesel and BD20 are 486ppm and 568 ppm respectively at full load. The NO emission decreased by 32% for DEE15 and 26% for DEE10 at full load compared with BD20 blend. The decrease in NO emission for DEE may be due to the high latent heat of vaporization of DEE results in cooling the charge [83].



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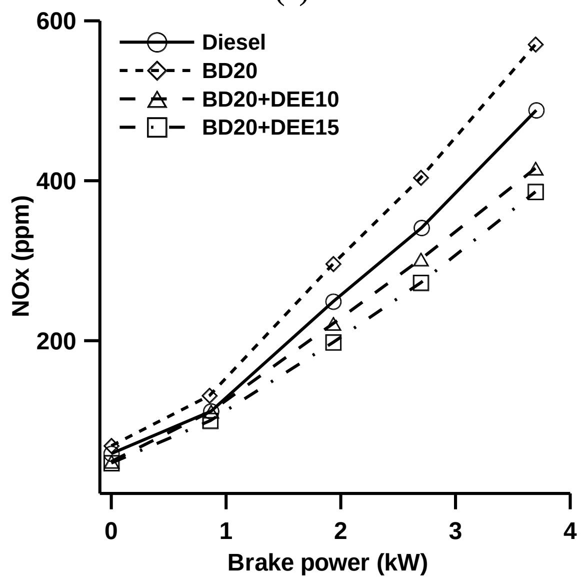
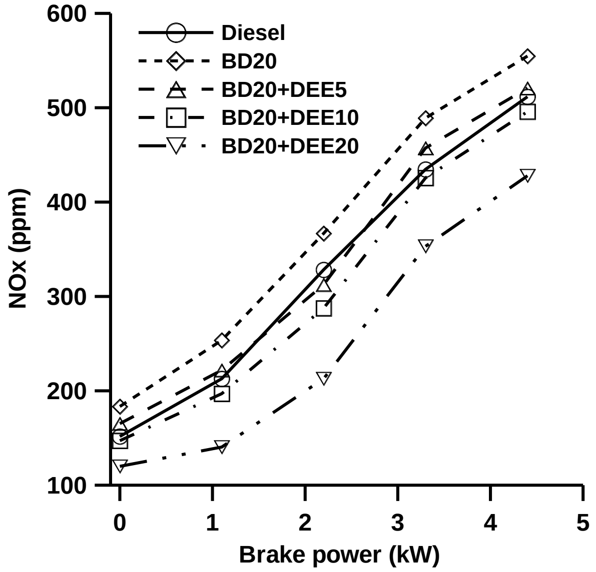


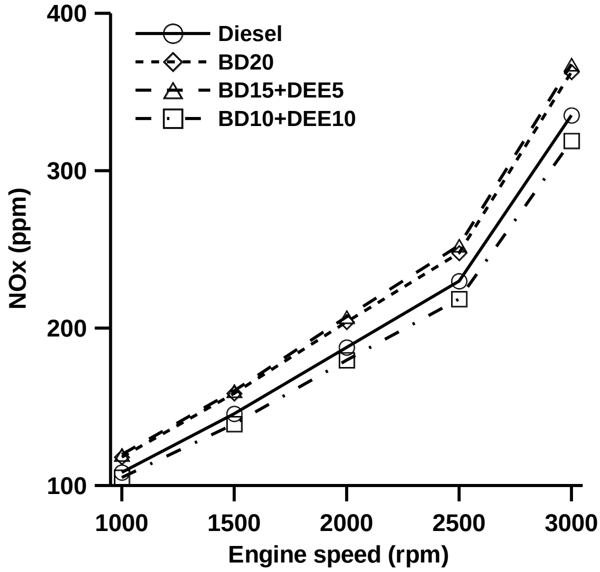
(b)

Fig. 13. Effect of diethyl ether additive on NOx emissions of diesel-biodiesel blends [81, 83]

The NOx concentration varies linearly with engine load as seen in Fig. 14(a). As the load increases, the overall fuel-air ratio increases, resulting in an increase in the average gas temperature in the combustion chamber, and hence NOx formation, which is sensitive to temperature increase. At all loads the emission NOx for BD20 is found to be maximum because all vegetable oils are oxygenated intrinsically.



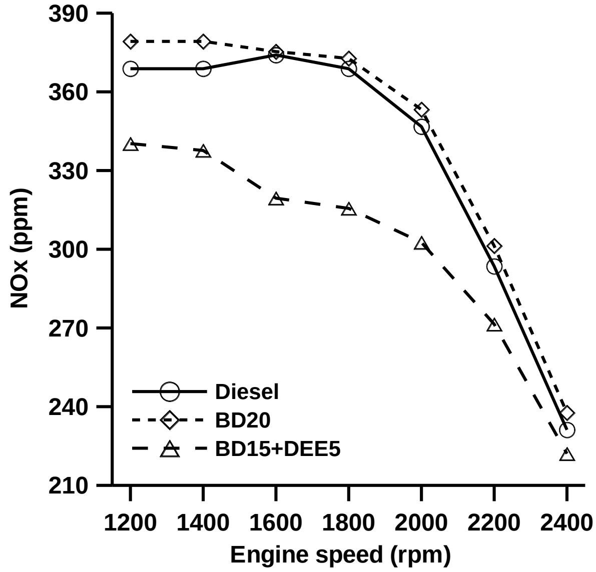
(a)



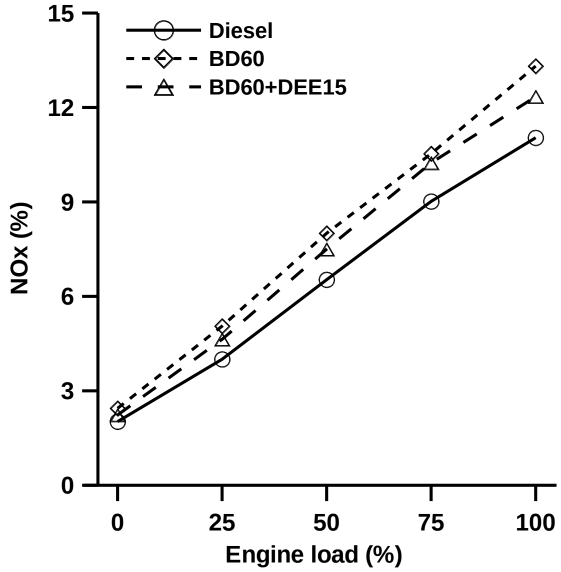
(b)

Fig. 14. Effect of diethyl ether additive on NOx emissions of diesel-biodiesel blends [87, 91]

When small quantities of additives like DEE is started adding the NOx content started reducing [87]. Fig. 14(b) illustrates the NO emission for test fuels. NO formation generally depends on oxygen concentration, air surplus coefficient, cylinder temperature and residence time. In this investigation, BD20 produced 8.2% higher NO emission on average than diesel. Higher NO for BD20 can be attributed to higher fuel bound oxygen. The higher oxygen content of biodiesel delivers higher local peak temperature which results in higher NO formation. Another reason which can be mentioned is the higher cetane number of biodiesel. Due to higher cetane number, combustion advances, combustion duration reduces and premixed part of the combustion increases where NO is formed mostly. BD15DEE5 produced slight increased and BD10DEE10 produced about 12% decreased NO emission than BD20. The higher oxygen content of the DEE blends was the most probable cause for such higher emission of NO. Nevertheless, an increased portion of DEE (BD10DEE10) reduced NO emission than BD20 primarily due to the higher latent heat of evaporation of DEE [91].



(a)



(b)

Fig. 15. Effect of diethyl ether additive on NOx emissions of diesel-biodiesel blends [98, 102]

Fig. 15(a) shows the comparative NOx emission of the diesel and fuel blends. As the speed decreased, NO emission of all the blends increased. It can be attributed to the higher available time span of combustion as the speed becomes lower. BD20 showed higher NOx because it contains a higher level of oxygen. However, though DEE has higher oxygen content, BD15DEE5 blend showed lower NO which can be explained by their lower calorific value and higher heat of evaporation which resulted in lower in-cylinder temperature. The lower NOx for BD15DEE5 blend can be also attributed to reduced part of premixed combustion where NO is mainly formed [98]. Fig. 15(b) shows the variation in NOx emissions at different loading conditions. It is observed from the figure that NOx emissions are increased with increase in engine load for all tested fuels. NOx emissions are considerably higher for BD60 blend. The reason biodiesel blend exhibits more NOx emissions is due to excess oxygen and favorable combustion temperature when compared to diesel. NOx is formed when the pressurized air inside the cylinder, having nitrogen constituent reacts with oxygen during combustion at higher temperatures. DEE15 blend showed lesser NOx emissions than BD60 blend at all tested conditions [102].

The parameters affecting the formation of NOx in a diesel engine are; the combustion duration, temperature, higher compression ratio, pressure and the availability of oxygen. The variation of NOx emission with a load for tested fuels depicted in Fig. 16(a). It can be observed from the figure that diesel exhibits the highest NOx emission. Due to the higher density of BD40, the combustion may be incomplete and result in a lower NOx emission for the given power output. The addition of DEE might reduce the cylinder temperature as a result of its higher latent heat of vaporization and this results in lower NOx emissions than that of diesel operation for the given power output. The NOx emission of DEE4 is approximately 25% lower compared to that of diesel, and about 20% higher compared to that of BD40 blend at full load [107]. Fig. 16(b) [110] shows the concentration of NOx for BD40E20, DEE5 and DEE10 fuel blends with brake power. NOx emissions are sensitive to oxygen content, adiabatic flame temperature (AFT) and fuel spray characteristics. In general, a fuel ensuring complete combustion will give higher cylinder temperature followed by more NOx formation. NOx is also formed as a result of thermal mechanisms during the diffusion combustion stage which causes higher in-cylinder temperature and pressure. Throughout the engine load conditions, DEE addition reduced the NOx invariably.

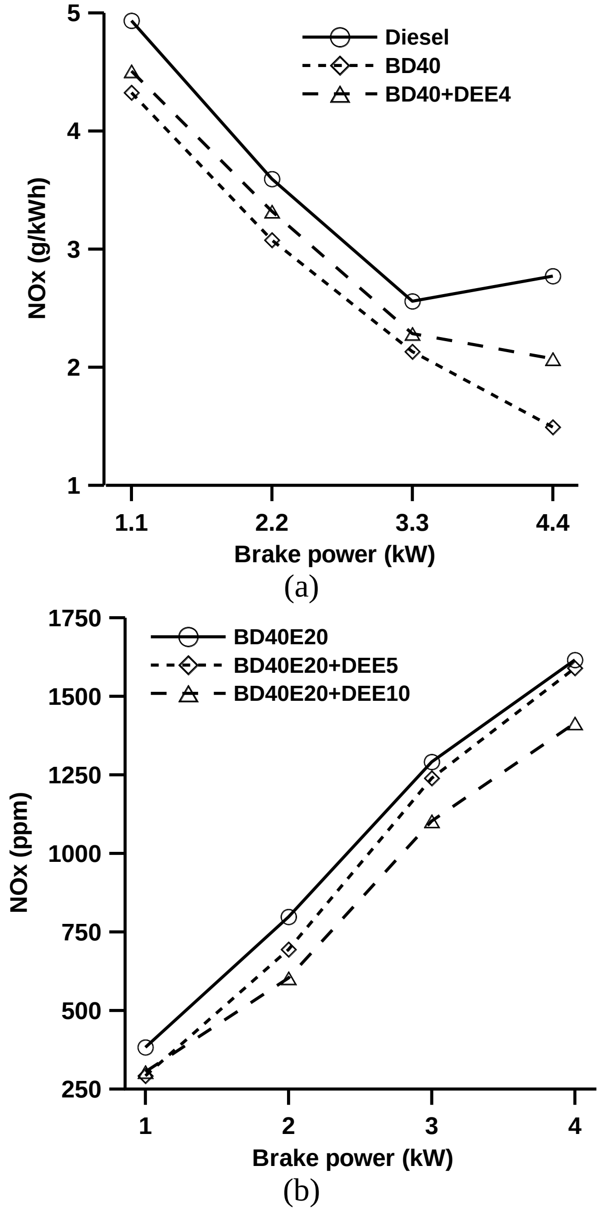


Fig. 16. Effect of diethyl ether additive on NOx emissions of diesel-biodiesel blends [107] and biodiesel-ethanol blend [110]

Numerical values about diethyl ether addition on NOx emissions are tabulated in Table 2. The ethyl ether addition into various diesel engine fuels provides the decreases in NOx emissions as seen in Table 2.

6. Conclusions

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

Table 2. Numerical values about diethyl ether addition on NOx emissions

Base fuel + Additive	NOx emissions (variation%)	Ref.
DEE	↓ 11.4 ↑164.4	[15]
D + 24% DEE	↓ 14.4-23.2	[17]
D + 20% DEE	↑ 11.7-44.4	[22]
D + 50% DEE	↑ 3.8-19.1	[23]
D + 5% DEE	↓ 1.3-9.9	[29]
D + 10% DEE	↑ 2-8.6	[29]
D + 15% BD + 5% DEE	↓ 3.8-23.5	[31]
D + 30% DEE	↓ 20.6	[32]
D + 10% E + 15% DEE	↓ 17.9-427	[33]
D + 15% E + 30% DEE	↑ 44.6-111.4	[35]
D + 15% DEE	↑ 5-23.6	[41]
D + 40% NG + 10% DEE	↓ 3.3-23.8	[46]
BD + 20% DEE	↓ 8.4-23.2	[50]
BD + 25% DEE	↓ 3.1-68.7	[53]
BD + 15% DEE	↑ 2.1-4	[59]
BD + 15% DEE	↓ 24.4-33.9	[64]
BD + 200 g/h DEE	↓ 5.1-12.4	[65]
BD + 170 g/h DEE	↓ 2.9-32.1	[66]
BD + 10% DEE	↓ 33.3-50	[67]
D + 20% BD + 15% DEE	↓ 2.7-17	[74]
D + 20% BD + 15% DEE	↓ 38.7-58	[76]
D + 20% BD + 5% DEE	↑ 3.1-7.1	[79]
D + 20% BD + 15% DEE	↓ 30.2-59.5	[81]
D + 20% BD + 20% DEE	↓ 22.8-44.6	[87]
D + 10% BD + 10% DEE	↓ 2.9-4.9	[91]
D + 15% BD + 5% DEE	↓ 3.9-14.6	[98]
D + 60% BD + 15% DEE	↑ 10.4-15.7	[102]
D + 40% BD + 4% DEE	↓ 7.6-25.3	[107]
D + 40% BD + 20% E + 10% DEE	↓ 3.9	[110]

- The formation of NOx is a function of flame temperature, the residence time of nitrogen at that temperature and local oxygen concentration in the combustion chamber.
- The properties of DEE which affect the NOx formation are high cetane number, oxygen content, low calorific value, the high latent heat of vaporization. The high cetane number provides a reduced ignition delay period and shortened combustion duration which reduce the NOx emissions. The oxygen content of DEE brings more zones near to stoichiometric conditions, these conditions favour for NOx formation. Additional oxygen results in more complete combustion and increases the temperature of the burned gas, which produces more NOx. Lower calorific value and high latent heat of vaporization resulted in lower cylinder temperatures which generate lower NOx.
- NOx emissions generally increase with the increase of engine load due to increasing combustion temperature while it decreases with increasing engine speed due to the less available time span of combustion.
- The use of alternative fuels i.e. ethanol and natural gas partially effective for the reduction of NOx. Exhaust gas recirculation strategy provides good control over the NOx emissions.
- The addition of diethyl ether to diesel fuel generally causes a reduction in most studies due to lower combustion temperatures. Some researchers reported that there is an increase in the NOx emissions with the addition of the DEE as it helps in complete combustion of the fuel resulting in an increase of combustion chamber temperature.

The addition of diethyl ether to various biodiesel fuels and biodiesel blends generally reduces by improving combustion due to its higher cetane value and available oxygen. Additionally, lower heating value and higher latent heat of vaporization of diethyl ether make an extra contribution to reducing of NOx.

Abbreviations

BD : Biodiesel
BD–D : Biodiesel–diesel blends
CDB : CNSO-Diesel blend
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
HCCI : Homogenous charge compression ignition
K : Kerosene
MTBE : Methyl tertiary butyl ether
NG : Natural gas
NOx : Nitrogen oxides
PCCI : Partially charge compression ignition

PM : Particulate matter
SOx : Sulphur oxides
THC : Total gaseous hydrocarbons

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