INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY
2019, VOL. 3, NO:1, 6-20
www.dergipark.gov.tr/ijastech

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

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Abstract

This study was compiled from the results of various researches performed on usage diethyl ether as a fuel or fuel additive in diesel engines. Three different methods have been 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 internal combustion engines are carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM) and smoke. 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 fuels. 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 usage 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 additive on the CO emissions.

Keywords: CO emissions; Diesel engine performance; Diethyl ether; Fuel additives

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Review Article

Manuscript
Received 03.01.2019
Revised 04.03.2019
Accepted 12.03.2019
Doi: 10.30939/ijastech..507799

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 form their high emission drawbacks like particulate matters (PM), total gaseous hydrocarbons (THC), nitrogen oxides (NOx), sulphur oxides (SOx) 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 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.

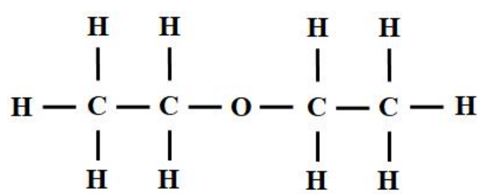

Fig. 1. Diethyl ether chemical composition [3]

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].

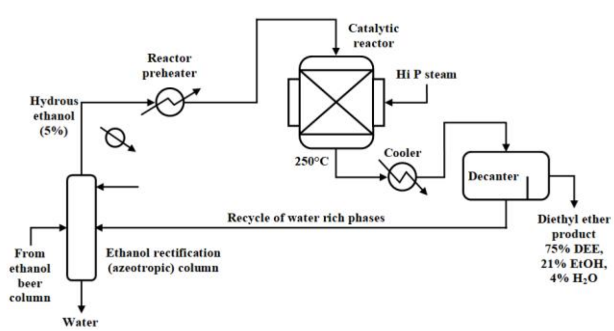

Fig. 2. Production of diethyl ether from ethanol [14]

As shown in Table 1, DEE has several favourable properties, including exceptional cetane number, reasonable energy density, high oxygen content, low autoignition temperature and high volatility. Therefore, it can be assisting in 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]. 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].

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
Autoignition 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

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 CO Emissions

Sezer [15] declared that CO emission became higher for the equal equivalence ratio condition, while it was lower at equal mass fuel injection condition for DEE. The reduction in CO emission can be attributed to lower carbon fraction and oxygen content of DEE. The lower carbon fraction resulted in lower incomplete combustion products and presence of oxygen in the fuel made an extra contribution to reduction of incomplete combustion products such as CO. However, increases in CO 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 leaded to dissociation reactions and abundant oxygen in combustion chamber contributed dissociation products such as CO. Rakopoulos et al [17] declared that CO emission of all DEE-diesel blends was lower than diesel fuel. The reduction was higher at higher percentage of DEE in the blend as seen in Fig. 3(a). Finally, the emitted CO followed the same behavior as the emitted soot by the engine, a fact collectively attributed to the same physical and chemical mechanisms affecting almost in the same way, at least qualitatively, the net formation of these emissions. Karthik and Kumar [21] declared that fraction of DEE was increased in the blends, the amount of CO decreased as seen in Fig. 3(b). Diesel fuel showed the highest CO, whereas DEE20 blend showed the least CO. Also, percentage of

EGR increased, the amount of CO did not vary much. Banapurmath et al [22] declared that CO is formed as a result of incomplete combustion. The variation of CO with load for different percentage of DEE blends was given in Fig. 4(a). CO emissions reduced with increased DEE ratio in diesel fuel while they increased with increased loading conditions. Lee and Kim [23] declared that CO forms as a result of incomplete combustion due to insufficient oxygen in the air-fuel mixture. The level of CO emissions is controlled primarily by the air-fuel equivalence ratio. CO of diesel and DEE blends showed similar trends to those of HC; these emissions tended to increase under lower engine loads. Under low load conditions, cylinder pressures and temperatures were low, and thus incomplete combustion occurred due to the low autoignitibility and the resulting increase in CO. Diesel fuel emitted more CO emissions than DEE blends due to lower autoignitability as seen in Fig. 4(b). The oxygen molecules in DEE blends helped to achieve complete combustion and oxidized the already formed CO to CO_2.

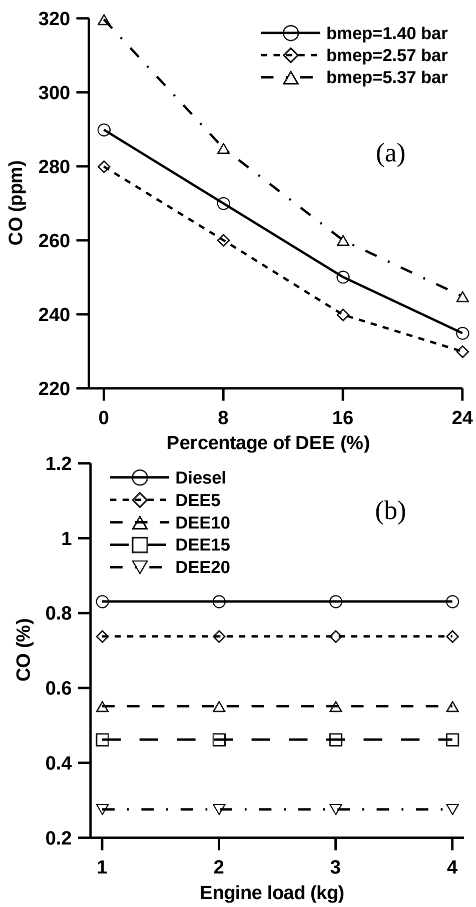

Fig. 3. Effect of diethyl ether additive on CO emissions of diesel fuel [17, 21]

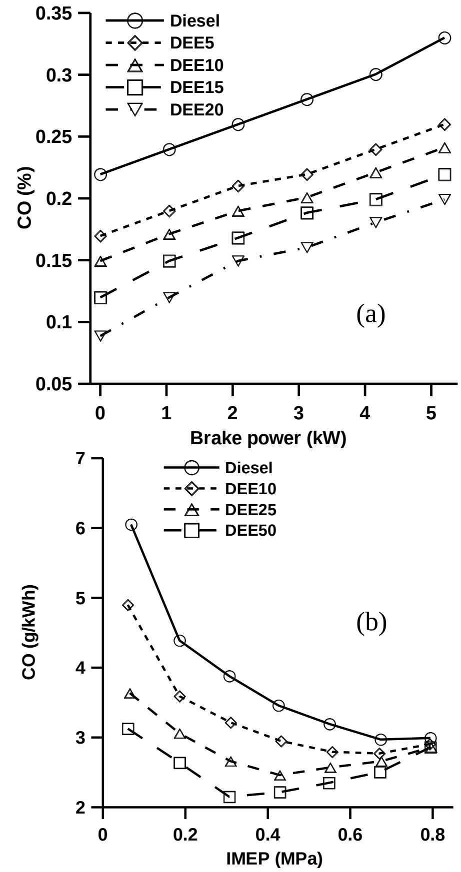

Fig. 4. Effect of diethyl ether additive on CO emissions of diesel fuel [22, 23]

Saravanan et al [24] declared that CO emissions increased slightly with blending of DEE. This resulted from the incomplete combustion of the fuel due to over leaning of the mixture. Madhu et al [29] declared that CO emission for DEE-diesel blend was more than the diesel fuel. There was an increase of 3% and 8% with DEE5 and DEE15 respectively when compared with diesel. This was due to the lean flame out region, lower temperatures and pressures exerted in the combustion chamber. As the injection pressure increased, CO emission also increased with addition of DEE. This was due to the high latent heat of vaporization of DEE which tended to produce slow vaporization and mixing of fuel. DEE, being a highly volatile liquid and less availability of oxygen and higher injection pressures could also be responsible for higher CO emissions. Prasadarao et al [31] declared that the engine emitted more CO for diesel as compared to biodiesel and other fuel blends at higher loads except for BD15DEE5 as seen in Fig. 5(a). This happened due to complete combustion inside the cylinder. The DEE addition into diesel and biodiesel fuels increased CO emissions. But, the BD15DEE5 blend presented the lowest CO emission at all load conditions due to the oxygen present in biodiesel and DEE aided for complete combustion.

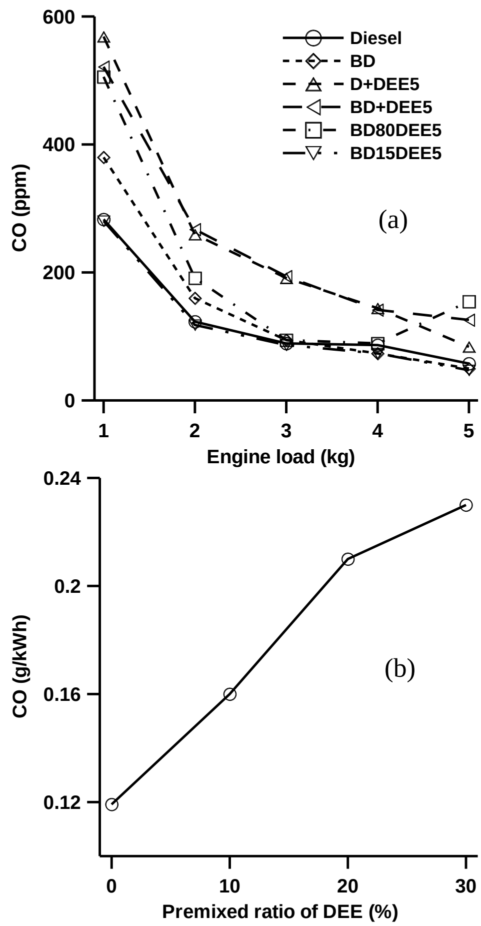

Fig. 5. Effect of diethyl ether additive on CO emissions of biodiesel-diesel blends [31] and diesel fuel [32]

Cinar et al [32] declared that HCCI engines generally suffer from higher CO and HC emissions. CO emissions were increased with increasing of DEE premixed ratio under HCCI-DI operating conditions, compared to neat diesel as seen in Fig. 5(b). CO emissions are primarily effected from equivalence ratio. CO emissions were increased with the increase of the global equivalence ratio. The global equivalence ratio was increased by 0.22, 0.236, 0.253, 0.275 and 0.31 for different premixed ratios from 0% to 40%, respectively. Also, lower combustion temperatures affected the oxidation of CO. CO emissions were increased by 91.6% with the premixed DEE ratio of 30% compared to neat diesel operation. Iranmanesh [33] declared that there was no significant difference between DEE blends and diesel fuel at lower loads, but an increase of CO emission was observed at higher loads for larger amount of DEE (more than 10%). The reason might be explained by the fact that besides the effect of high latent heat of vaporization that leads to temperature reduction, the theory of CO formation held that, in the premixed combustion phase, the CO concentration increased rapidly to the maximum value in the flame zone. The CO formed via this path was then oxidized to CO_2 but at a slower rate. Therefore, one possible explanation for the increase of CO by addition of large amount of DEE was injection timing delay and consequently retarding onset of combustion, hence less time was available for the oxidization process and leaving more CO in the exhaust. Moreover, the erratic operation of the engine with high amount of DEE addition might be another reason of CO formation due to rough burning and miss firing. However, the blend E10DEE8 exhibited the lowest CO emission and showed improvement CO compared with diesel fuel by 4.38%. Sudhakar and Sivaprakasam [35] declared that CO emission for E15 blend was slightly higher than pure diesel. The increased injected percentage of DEE increased CO emissions marginally as seen in Fig. 6(a). This was due to excess oxygen available in diethyl ether enhance the inlet air condition. The CO emissions were increased by 37%, 90% and 100% at full load conditions respectively for 10, 20 and 30 percent DEE injections. Sudhakar and Sivaprakasam [36] declared that the increasing percentage of DEE injection resulted marginal increase in CO emission. The exhaust gas recirculation (EGR) system further increased the CO emission at full load conditions. Paul et al [37] declared that CO emission increased by DEE5 blend. However, with the addition of ethanol, it again decreased significantly. This decrease might be due to the lower C/O ratio of DEE and ethanol. Due to this, a few carbon radicals were participating in combustion. Along with that, the oxygen released by the decomposition of the two additives also helped in oxidation of the carbon to CO_2. It was also observed that CO emission increased significantly with DEE10 blend. Adding ethanol with DEE10 blend was found to improve CO emission significantly. Patnaik et al [41] declared that the DEE15 blend indicated a drastic reduction in CO emission about 62% less than diesel at full load as seen in Fig. 6(b). This can be attributed to DEE addition which improved the start of ignition and suppressed the ignition delay due to its low boiling point and viscosity that helped in proper mixing with air leading to early burning and allowed more time for oxidation of fuel. The molecular oxygen in DEE also improved the combustion leaded to better oxidation of the fuel air mixture. The higher cetane number of DEE acted as an ignition enhancer reduced the combustion duration indicating improved rate of combustion, resulting in a reduced CO.

Karabektas [46] declared that the use of natural gas as a dual fuel (NG40) yielded a considerable increase in the CO emissions particularly at low and medium loads in comparison by diesel fuel. It was due to poor fuel utilization and oxidation with natural gas usage at dual fuel mode operation in diesel engines. On the other hand, the use of DEE with NG40 cause lower CO emissions compared with NG40 as seen in Fig. 7(a). The higher content of DEE resulted in the lower the CO emissions. The use of NG40DEE10 yielded the lowest CO emissions compared with other dual fuels. The oxygen content in DEE increased the oxygen concentration in the cylinder, thus making a positive effect on decreasing CO emissions. Moreover, high cetane number of DEE additive shortened the combustion duration and improved the combustion, thus yielding lower CO emissions. Rakopoulos [50] declared that CO emitted by DEE blends was lower than those of neat biodiesel and diesel as seen in Fig. 7(b). This might be attributed to the presence of extra fuel-bound oxygen in the DEE blends even at locally fuel-rich zones, which seemed to have the dominating influence. Nonetheless, it should be noted that the emitted CO level by diesel engines is already small.

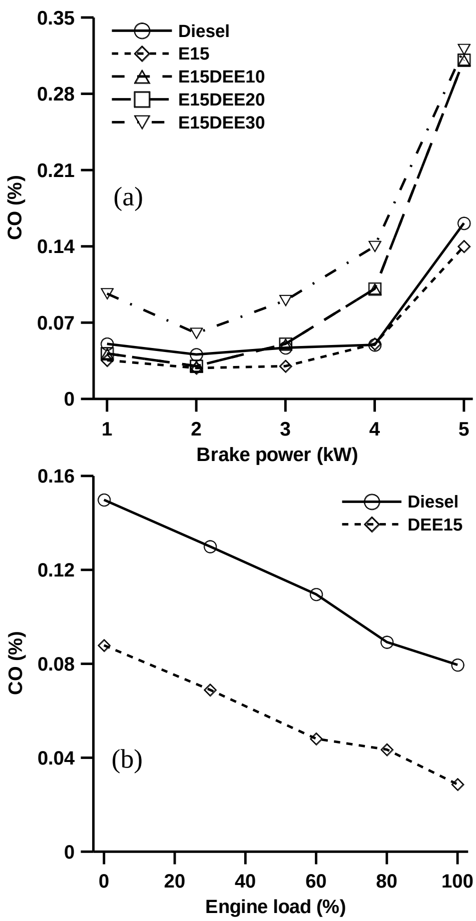

Fig. 6. Effect of diethyl ether additive on CO emissions of ethanol-diesel blends [35] and diesel fuel [41]

Krishna et al [53] declared that CO emissions for DEE blends with Karanja oil were lower than values for biodiesel as seen in Fig. 8(a). The CO emissions of 25% DEE blends with karanja oil operation have been found to be 0.045 ppm as compared to 0.055 ppm of pure karanja oil and 0.035 ppm of pure diesel respectively. A possible explanation for the increase in CO emissions at high loads could be the problem of air fuel mixing, due to difficulty in atomization and vaporization of the vegetable oil and its blends. This difficulty in atomization was due to higher viscosity of the vegetable oil. This caused locally rich mixtures and hence more of incomplete combustion during the late combustion phase. Further, at higher loads, the fuel- air mixture was also richer, thus causing difficulty in atomization and inherently more CO was produced. Sivalakshmi and Balusamy [59] declared that CO emission decreased by 25% for DEE5 blend comparing to that of biodiesel. This was due to the improvement of spray atomization and fuel-air mixing. The improvement in spray atomization and fuel-air mixing decreased the rich region in the cylinder and decreased the CO emission. Moreover, the high temperature helped the CO oxidation in the cylinder. The CO emissions of DEE10 were higher than those of biodiesel at lower and medium loads and same as biodiesel at full load as seen in Fig. 8(b). In case of DEE15 blend, the CO emissions increased at all loads due to incomplete combustion of the fuel. Moreover, the mixture that is near the cylinder walls or crevices, where the flame will not penetrate, mix with the hot combustion gases during the latter part of the power stroke and also in the exhaust manifold, oxidation reactions occur, but do not have time to undergo complete combustion.

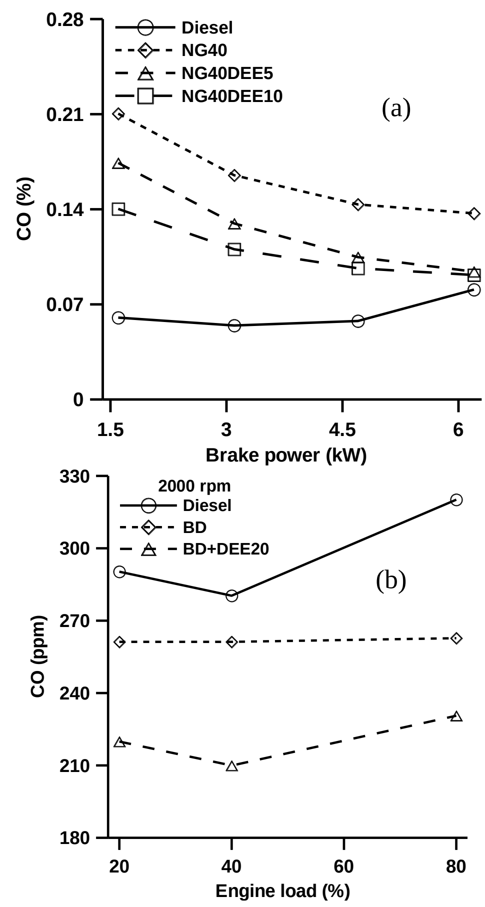

Fig. 7. Effect of diethyl ether additive on CO emissions of natural gas-diesel dual fuel [46] and biodiesel fuel [50]

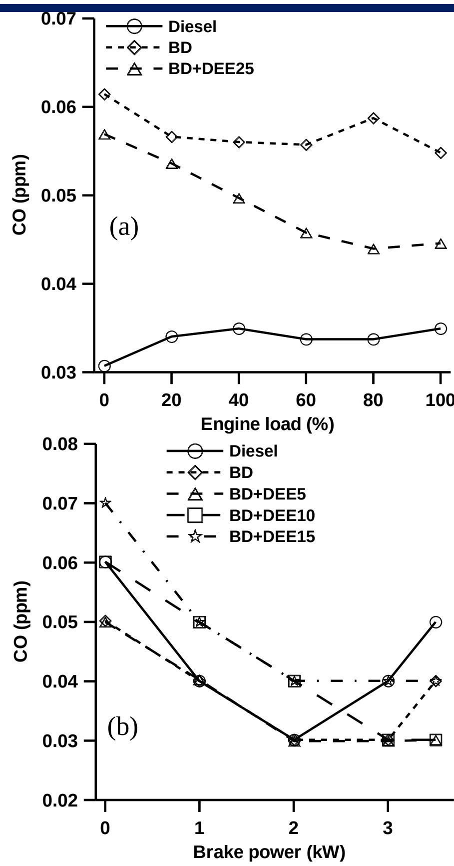

Fig. 8. Effect of diethyl ether additive on CO emissions of biodiesel fuels [53, 59]

Rajan et al [64] declared that CO emissions increase with an increase in DEE concentrations at all loads compared with neat biodiesel. This may be due to high latent heat of vaporization of DEE resulting in cooling the charge at full load compared with biodiesel. As seen in Fig. 9(a), 27% decrease in CO emission for 15% DEE blend might be due to the presence of more oxygen (21.6% by mass) in DEE and biodiesel (11% by mass), which made the combustion complete, resulting in lower CO emission at high loads compared with diesel. Geo et al [65] declared that CO emission was about 4.6 g/kWh with diesel at maximum power output. The higher CO emission was observed with biodiesel at all outputs as compared to diesel as seen in Fig. 9(b). The maximum CO was 6.7 g/kWh with biodiesel at peak power output. This increase in CO emission was due to lower air fuel ratio of biodiesel (12.4:1) compared with diesel (14.5:1). The low volatility of biodiesel affected the atomization process, resulting in local rich mixtures, which produced higher CO emission. However, the addition of DEE with biodiesel resulted in reduced CO emission. The CO emission was about 4.9 g/kWh at the DEE flow rate of 200 g/h. The early injection of DEE made the mixture homogeneous before the injection of biodiesel. The ignition improver (DEE) formed a number of ignition centers in the combustion chamber which resulted in complete combustion. This leaded to reduced CO emissions. Hariharan et al [66] declared that the mixture of DEE-air, which filled the cylinder, was very lean and the flame would not propagate. When this mixed with the hot combustion gases during the later part of the power stroke and also in the exhaust manifold, oxidation reaction occurred but did not undergo combustion. Therefore, increase in CO emissions occurred due to the increased amount of DEE presented in the quench layer and crevice regions. CO for diesel is lesser than biodiesel-DEE operation as seen in Fig. 10(a). Devaraj et al [67] declared that the amount of CO emitted from diesel varied from 0.07% at 20 percent load and 0.08% at full load as seen in Fig. 10(b). For biodiesel, it varied from 0.06% at 20 percent load and 0.14% at full load. For DEE5 and DEE10, the values were same 0.09% at 20 percent load and at full load are 0.13% and 0.12% respectively. For biodiesel, the amount of CO was increasing with the increment in the load. The reason for the increase in CO in case of biodiesel was less in cylinder temperature. The decrease in CO at full load was when the mixture was getting increased from DEE5 to DEE10. This might be due to the availability of oxygen was more, when DEE was added to biodiesel.

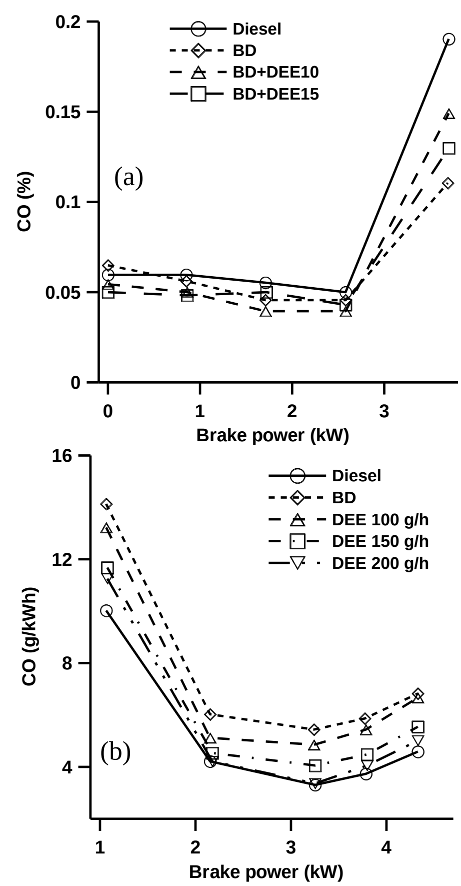

Fig. 9. Effect of diethyl ether additive on CO emissions of biodiesel fuels [64, 65]

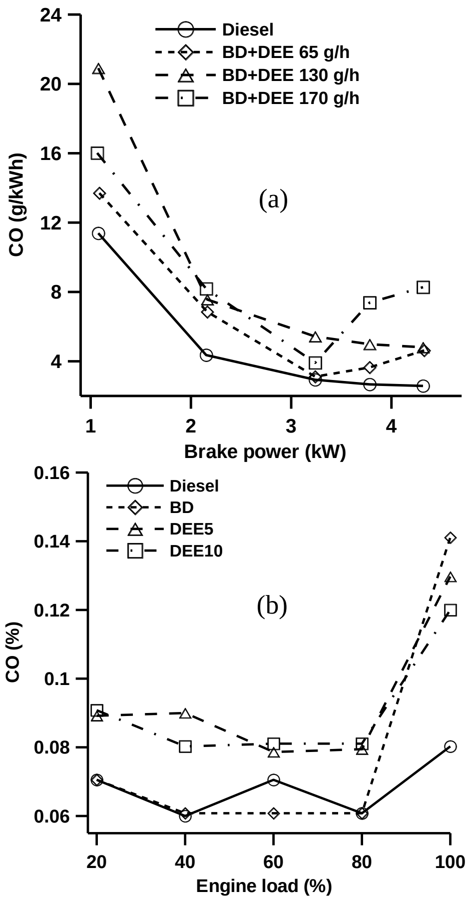

Fig. 10. Effect of diethyl ether additive on CO emissions of biodiesel fuels [66, 67]

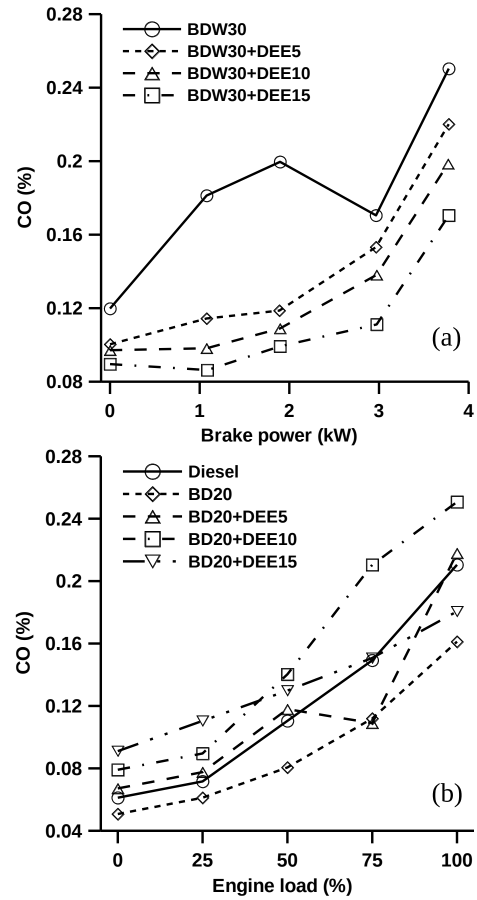

Fig. 11. Effect of diethyl ether additive on CO emissions of water-biodiesel emulsified fuel [70] and diesel-biodiesel blends [74]

Sachuthananthan and Jeyachandran [70] declared that as DEE percentage increased CO emission decreased as seen in Fig. 11(a). For 30% water-biodiesel emulsion CO emission was 0.25 % and for 10% DEE it was 0.2 % and for 15%DEE it was 0.17% at full load. This reduction in CO emission was due to the fact that DEE was an oxygenated compound contained 21.6% oxygen by mass which was the main reason for the complete combustion of air and fuel mixture which reduced the CO emission. Kumar et al [74] declared that CO emission of CI engine is low due to lean mixture operations. It strongly depends on the air fuel ratio. The CO emission is higher for neat biodiesel than its blends and diesel, due to poor atomization of BD as seen in Fig. 11(b). From the result it was observed that CO percentage decreases in BD20 with respect to BD20DEE15 which was 11.11%. Also in diesel and B20 it increased by 23.8% by volume.

Ganesha and Chethan [75] declared that CO emission increased with changing load by observing Figure 12(a) for diesel has maximum CO emission in all load compared with BD10 blend. Minimum emission occurs for BD10DEE20 is 0.0028%, 0.0045%, 0.007%, 0.01% and 0.019%. As compared with BD10 and BD10DEE20 decrease CO emission is 42.85%, 77.78%, 71.42%, 60% and 21.52%. Srihari et al [76] declared that CO emission for the BD20 blend was far higher than that of diesel for all loads as seen in Fig. 12(b). Further, DEE5, DEE10 and DEE15 blends did not produce any reduction in CO emissions when compared to that of diesel and it almost remained same with diesel. However, it was seen that using DEE with the BD blend was far better than using a simple biodiesel-diesel blend.

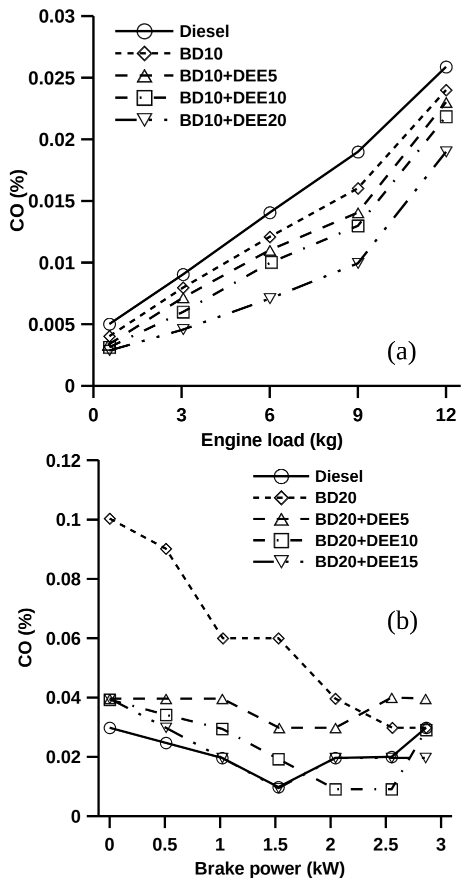

Fig. 12. Effect of diethyl ether additive on CO emissions of diesel-biodiesel blends [75, 76]

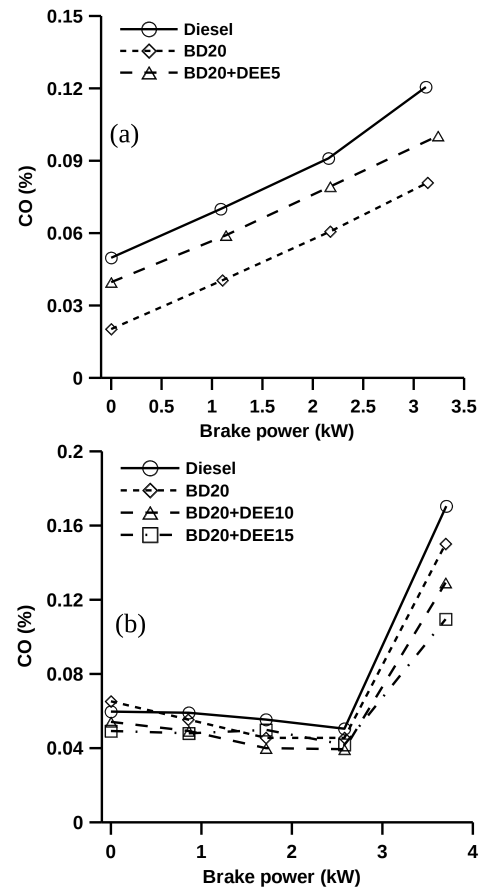

Fig. 13. Effect of diethyl ether additive on CO emissions of diesel-biodiesel blends [79, 83]

Abraham and Thomas [79] declared that formation of CO emission mainly depends upon the physical and chemical properties of the fuel used. When compared with diesel CO emission was much lower for BD20 and DEE5 blend as seen in Fig. 13(a) due to additional availability of oxygen, so complete combustion take placed. The CO emissions decreased with increase in DEE concentrations at all loads compared to BD20 as seen in Figure 13(b). This may be due to high latent heat of vaporization of DEE results in cooling the charge. It was observed that the CO emission of DEE10 and DEE15 are 0.15% and 0.13%, whereas for diesel and BD20 are 0.17% and 0.15% respectively at full load. The decrease in CO emission for DEE blends may be due to the presence of more oxygen in DEE and biodiesel, which makes the combustion complete, resulting in lower CO emission at high loads compared to diesel [83].

Fig. 14(a) shows the variation of carbon monoxide emissions. CO emission increases with increase in load. This is typical with all internal combustion engines since the air-fuel ratio decreases with increase in load. With increasing DEE percentage in the blend, CO emission level is decreased for 5% DEE and thereby increases up to 20% DEE due to poor combustion [87]. CO emission for the test fuels at different engine speed has been illustrated Fig. 14(b). BD20 produced a reduced emission compared to diesel all over the speed range. BD15DEE5 and BD10DEE10 reduced the CO emission than BD20 about 11% and 20.6% respectively because of more oxygen content. Therefore, lower density and viscosity of the modified blends increased the atomization efficiency and on top of that higher oxygen content really assisted complete oxidation of the fuels, hence reduced CO emission [91].

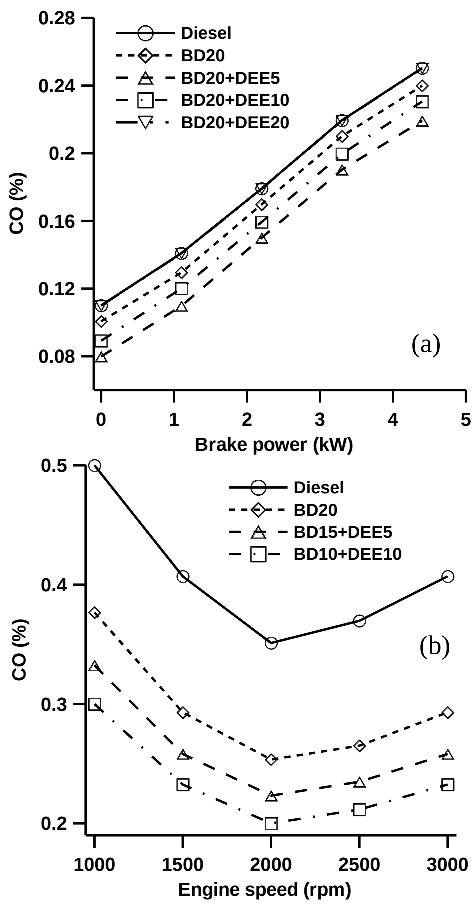

Fig. 14. Effect of diethyl ether additive on CO emissions of diesel-biodiesel blends [87, 91]

Fig. 15(a) shows the emission of CO of the blends. CO emission of BD20 is much lower than diesel fuel which can be attributed to the higher fuel bound oxygen. BD15DEE5 showed even lower CO emission than BD20 because of their superior level of oxygen content. Extra fuel bound oxygen in the blends ensures the oxidation of CO even on locally fuel rich zones which helps to reduce CO emission. However, different level of CO emission among the blends with additives can be explained by the physical and chemical properties of the additives [98]. The variation in CO emissions with respect to engine load is seen in Fig. 15(b). CO emissions are resulted from incomplete combustion of fuel. CO reacts with excess oxygen to form CO_2 by complete combustion. CO emissions are produced from the burnt fuel when the fuel air mixture is rich than stoichiometric. Another important reason for CO formation is due to lower flame temperature. The CO emissions are low for the blend DEE15. Diesel is having higher CO emissions when compared with other fuels. Lesser CO emissions are observed due to rich oxygen content in biodiesel. Thus, it is inferred that the introduction of diethyl ether to the biodiesel blend has helped in attaining complete combustion for the tested fuels [102].

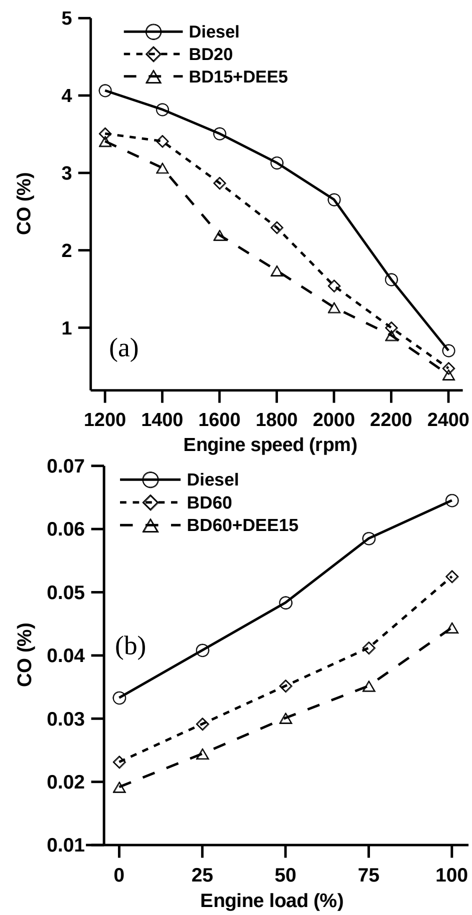

Fig. 15. Effect of diethyl ether additive on CO emissions of diesel-biodiesel blends [98, 102]

CO emission is indication of the incomplete combustion of the fuel-air mixture. CO is generated, when an engine is operated with a rich mixture. Diesel engines generally produce lower CO emission as they run on lean mixture. Fig. 16(a) shows the variation of CO emission with brake power. It is observed from the figure that as the load increases the CO emission decreases and at full load again increases. This is due to a full load more fuel supply, which provide rich zone and CO emission is occurred. The CO emission is the highest for BD40. However, the addition of DEE to the BD40 blend results in reduced CO emission, which is due to more oxygen being available for combustion than BD40. At full load, DEE4 gives lower CO emission of about 45% compared with BD40 blend [107]. Variation of CO emissions for all test fuels with respect to brake power is illustrated in Fig. 16(b). CO emissions from IC engines are controlled by the fuel/air equivalence ratio. Diesel fuel operates well on the lean side of the stoichiometric and hence formation of CO is low enough to be considered unimportant. Also, CO formation depends upon the physical-chemical properties of the fuel. The effect of alcohol and ignition improver changes the fuel spray characteristics, oxygen content, oxidation rate, cylinder temperatures and ignition center formation which influences the formation of CO. Higher CO is observed for DEE5 and DEE10 blends especially high engine load condition. The possible reason could be the promotion of lower temperature combustion (LTC) with DEE addition, even at higher engine loads. Addition of oxygenate blends promotes LTC and this lower temperature may not be sufficient for further oxidation of CO molecules trapped in the engine cylinder thereby resulting in higher CO emissions [110].

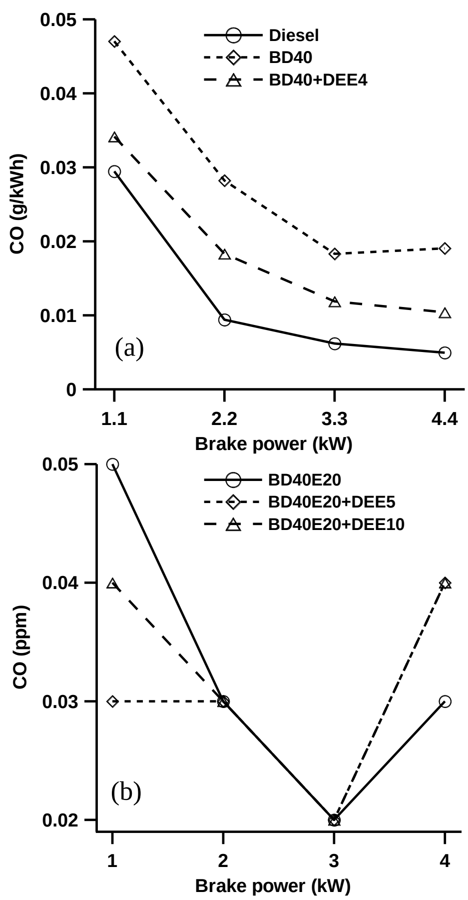

Fig. 16. Effect of diethyl ether additive on CO emissions of diesel-biodiesel blends [107] and biodiesel-ethanol blend [110]

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

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

Base fuel + Additive	CO emissions (variation%)	Ref.
DEE	↓ 51.6 ↑ 87.8	[15]
D + 24% DEE	↓ 17.8-23.4	[17]
D + 20% DEE	↓ 66.8	[21]
D + 20% DEE	↓ 39.6-59.6	[22]
D + 50% DEE	↓ 4.4-48.3	[23]
D + 15% BD + 5% DEE	↓ 0.9-18.2	[31]
D + 30% DEE	↑ 93	[32]
D + 15% E + 30% DEE	↑ 47.8-182.1	[35]
D + 15% DEE	↓ 41.3-63.9	[41]
D + 40% NG + 10% DEE	↓ 13.3-132.8	[46]
BD + 20% DEE	↓ 24.2-27.9	[50]
BD + 25% DEE	↑ 27.5-85.3	[53]
BD + 15% DEE	↓ 19.8 ↑ 32.9	[59]
BD + 15% DEE	↓ 9.5-31.8	[64]
BD + 200 g/h DEE	↑ 1.6-12.2	[65]
BD + 170 g/h DEE	↑ 33.3-220.7	[66]
BD + 10% DEE	↑ 14.9-49.5	[67]
BD + 30% W + 15% DEE	↓ 25.2-50.3	[70]
D + 20% BD + 15% DEE	↓ 14.2 ↑ 54.1	[74]
D + 10% BD + 20% DEE	↓ 26.6-49.7	[75]
D + 20% BD + 15% DEE	↓ 34.1 ↑ 32.9	[76]
D + 20% BD + 5% DEE	↓ 12.8-20.3	[79]
D + 20% BD + 15% DEE	↓ 10-35.7	[83]
D + 20% BD + 20% DEE	↓ 0.05-0.1	[87]
D + 10% BD + 10% DEE	↓ 40-43	[91]
D + 15% BD + 5% DEE	↓ 16.1-52.4	[98]
D + 60% BD + 15% DEE	↓ 31.2-42.4	[102]
D + 40% BD + 4% DEE	↑ 15.9-110	[107]
D + 40% BD + 20% E + 10% DEE	↓ 20 ↑ 33.3	[110]

5. Conclusions

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

- CO emission is indication of the incomplete combustion of the fuel-air mixture. CO is generated when an engine is operated with a rich mixture. Diesel engines generally produce lower CO emission as they run on lean mixtures.
- CO emission increases with the increase of engine load. This is typical with all internal combustion engines since the fuel-air ratio increases with increase in engine load. Additionally, CO emission is low for medium engine speeds in comparison with low and high engine speeds due to lean mixture operations.
- The formation of CO emission mainly depends upon the physical and chemical properties of the used fuel. The lower density and viscosity of diethyl ether increases the atomization efficiency and oxygen available in diethyl ether assists complete oxidation of the fuel. Additionally, CO emission reduces by diethyl ether addition as a few carbon radicals participate in

combustion because of the lower carbon fraction of diethyl ether.

- Diethyl ether addition improves the start of ignition and suppresses the ignition delay due to its low boiling point and viscosity that helps in proper mixing with air leading to early burning and allows more time for oxidation of fuel. Diethyl ether as the ignition improver forms a number of ignition centers in the combustion chamber which result in complete combustion. All of these lead to reduced CO emission. Moreover, high cetane number of diethyl ether shortens the combustion duration and improves the combustion, thus yielding lower CO emission.
- The higher combustion temperatures sourced from complete combustion and excess oxygen available in diethyl ether result in the increases in CO emission. The higher combustion temperature leads to dissociation reactions and abundant oxygen in combustion chamber contributes dissociation products such as CO.
- Another important reason for CO formation is lower flame temperature due to high latent heat of vaporization of diethyl ether. Additionally, the incomplete combustion of fuel due to over leaning of the air-fuel mixture causes an increase in CO emission. Moreover, the mixture that is near the cylinder walls or crevices, where the flame will not penetrate, mix with the hot combustion gases during the latter part of the power stroke and also in the exhaust manifold, oxidation reactions occur, but do not have time to undergo complete combustion.
- The increase in CO emissions can be the problem of air-fuel mixing, due to difficulty in atomization and vaporization of a vegetable oil and biodiesel. This difficulty in atomization is due to higher viscosity of the vegetable oil causes locally rich mixtures and hence more of incomplete combustion. The lower density and viscosity of diethyl ether increases the atomization efficiency and the oxygen molecules in diethyl ether helped to achieve complete combustion and oxidized the already formed CO to CO_2.

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
W : Water

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