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Conference Article

A Review Study on the Using of Diethyl Ether in Diesel Engines: Effects on HC 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 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 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 additive on the HC emissions.

Keywords: Diesel engine performance, Diethyl ether, Fuel additives, HC emissions.

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 seems 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

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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.

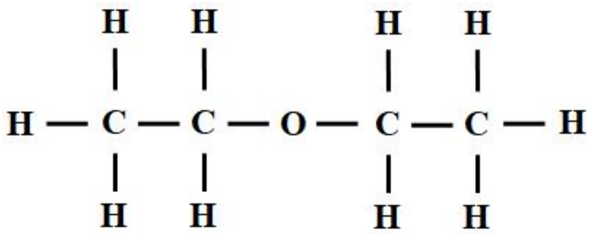


Fig. 1. Diethyl ether chemical composition [3]

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].

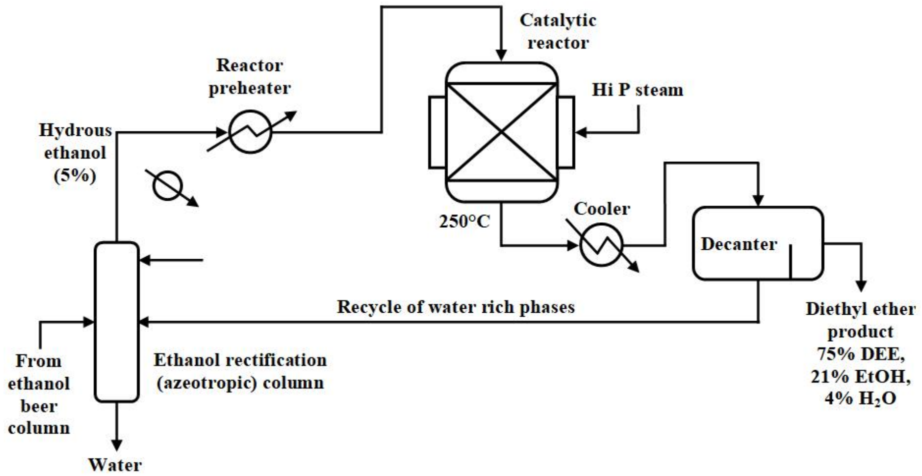


Fig. 2. Production of diethyl ether from ethanol [14]

As shown in Table 1, DEE has several favorable properties, including exceptional cetane number, reasonable energy density, high oxygen content, low 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

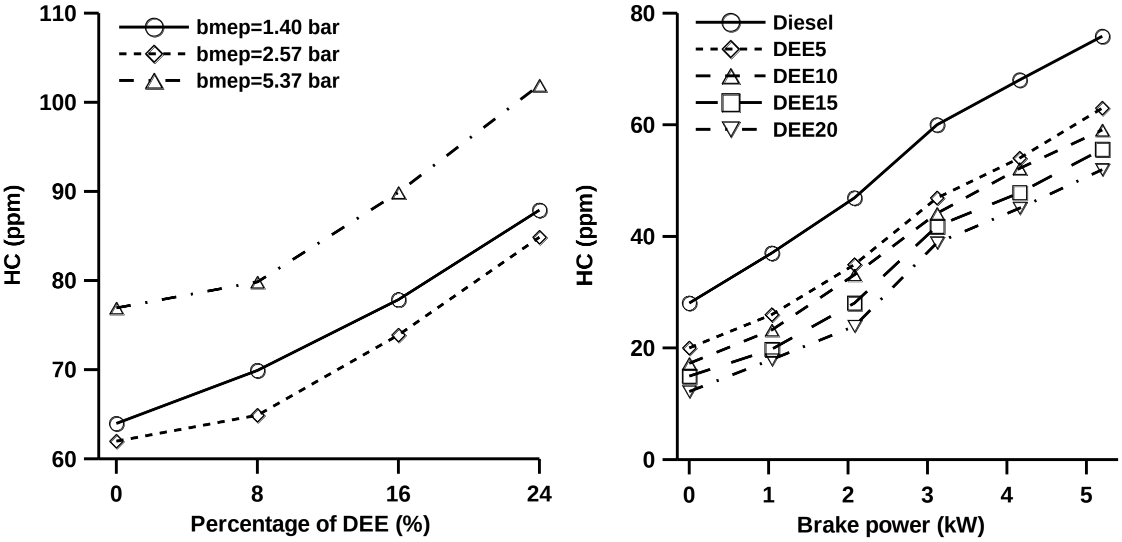
*NTP: Normal temperature and pressure

3. Studies on Diethyl Ether in Literature

There are several studies in the literature on the use 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].

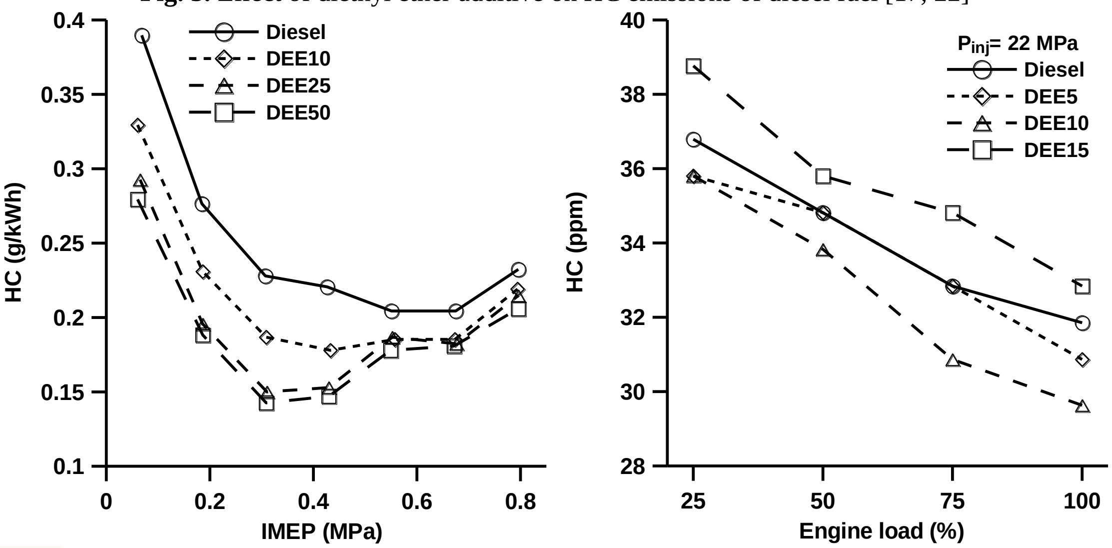
4. Effects of Diethyl Ether on HC Emissions

Rakopoulos et al [17] declared that HC emitted by all DEE-diesel blends was higher than diesel fuel, with the increase being higher the higher the percentage of DEE in the blend as seen in Fig. 3(a). The formation of unburned hydrocarbons originated from various sources in the engine cylinder. The higher heat of evaporation of the DEE blends causing slower evaporation and so slower and poorer fuel-air mixing, the increased spray duration causing unwanted fuel impingement on the combustion chamber walls and so flame quenching and mainly the increase of the so called ‘lean outer flame zone’ where flame is unable to exist. The latter one refers to the envelop of the spray boundary where the fuel has already mixed beyond the lean flammability limit during the ignition delay period and, thus, will not be able to auto-ignite or sustain a fast reaction front. Its effect is stronger the higher the ignition delay, as it is actually the present case with the DEE blends possessing increased ignition delays. Banapurmath et al [22] declared that HC is partially burned and unburned fuel emission. The variation of HC with load for different percentage of DEE blends was given in Fig. 3(b). HC emissions reduced with increased DEE concentration in diesel fuel while they increased with increased loading conditions.



(a) (b)

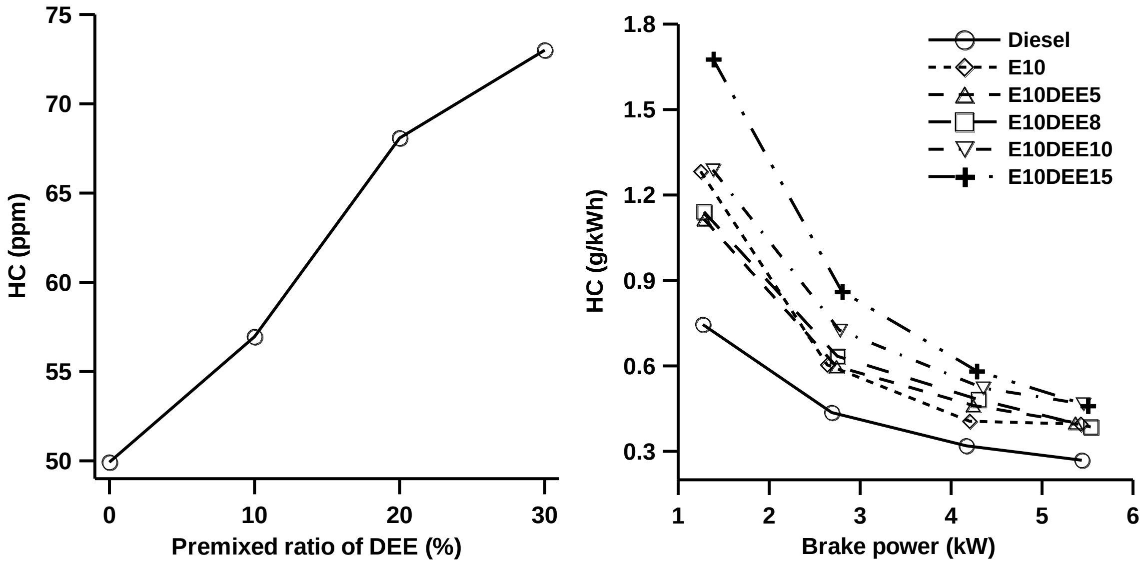
Fig. 3. Effect of diethyl ether additive on HC emissions of diesel fuel [17, 22]



(a) (b)

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

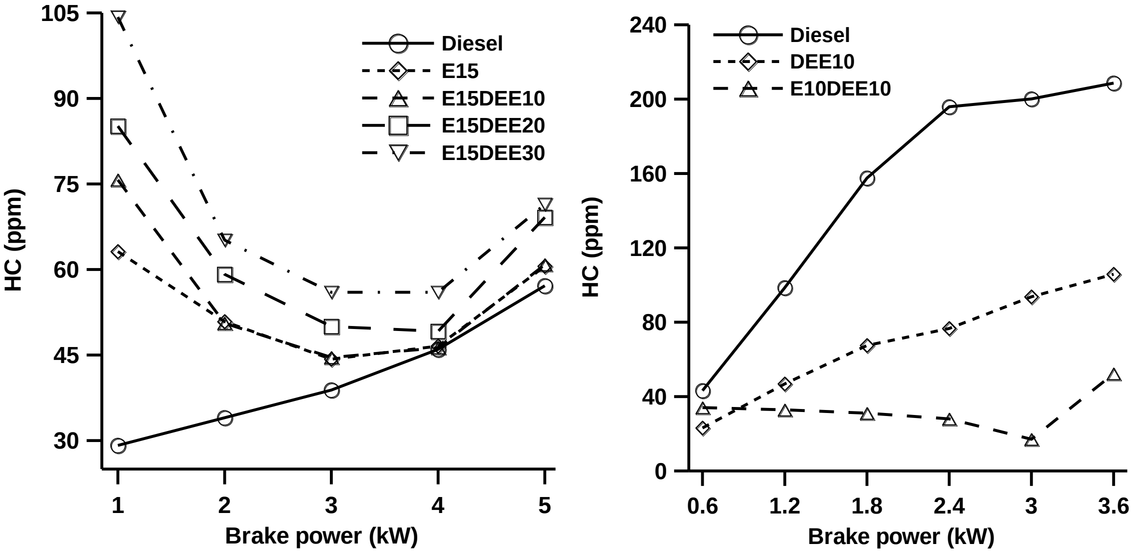
Lee and Kim [23] declared that HC emissions for DEE blends were lower than pure diesel especially for lower engine loads, and they decreased with increasing in DEE content in the blends as seen in Fig. 4(a). Over-leaning of fuel injected during the ignition delay period is a significant source of hydrocarbon emissions, especially under low engine load conditions where the ignition delay is long. As the autoignitability of DEE is significantly better than diesel, DEE exhibited a shorter ignition delay period, resulting in better combustion and a decreased HC for the DEE blends. Another reason for the low HC observed for the blends was that the higher oxygen content in the blends helped to combust the unburned fuel in the combustion chamber during the diffusion flame phase. Saravanan et al [24] declared that HC emissions increased with the addition of DEE. DEE has a higher cetane number (~125) but when blended with diesel its cetane number decreased and ignition delay period prolonged. The higher ignition delay period formed more HC emissions. The reduction in peak cylinder temperature might also contribute to the increase of HC emissions. Madhu et al [29] declared that HC emissions produced by DEE blends were more than the diesel fuel as seen in Fig. 4(b). There was 30% increase in HC emission with DEE15 at 20MPa pressure and as the injection pressure increases, HC emission increased with addition of DEE to diesel. This was due to the high latent heat of vaporization of DEE which tended to produce slow vaporization and mixing of fuel and air along with rare availability of oxygen at full load conditions leaded to incomplete combustion.



(a) (b)

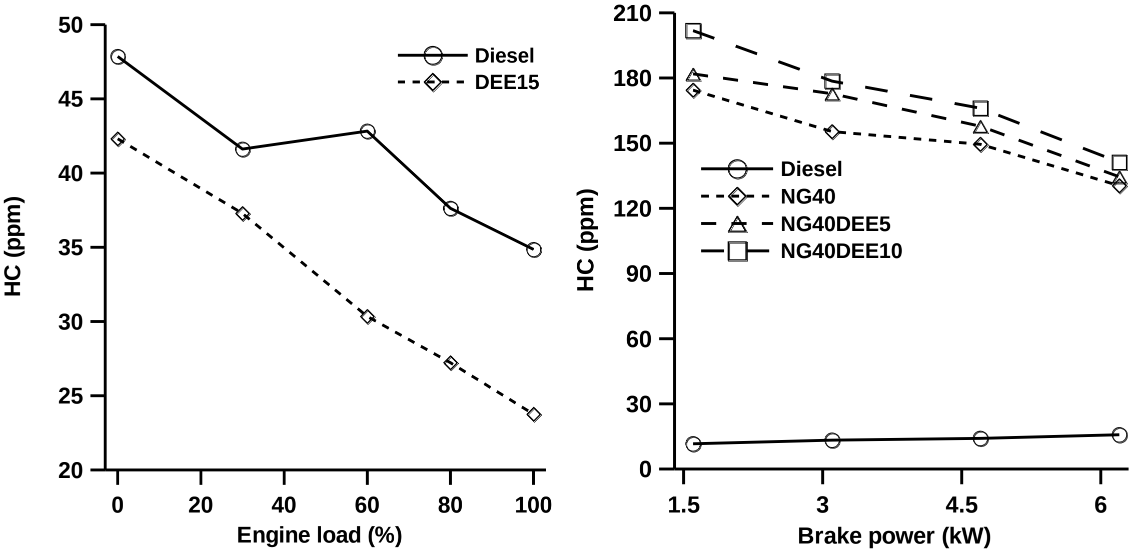
Fig. 5. Effect of diethyl ether additive on HC emissions of diesel fuel [32] and ethanol-diesel blends [33]

Cinar et al [32] declared that HCCI engines generally suffer from higher CO and HC emissions. HC emissions were increased with increasing of DEE premixed ratio under HCCI-DI operating conditions, compared to neat diesel as seen in Fig. 5(a). During the compression period, the premixed fuel charge trapped in the cylinder crevices influenced the increase in HC emissions. HC emissions were increased by 44% with the premixed ratio of 30% compared to neat diesel operation. Iranmanesh [33] declared that HC emissions had a moderate increase for the ethanol and all DEE additions to the diesel fuel at higher loads but it increased marginally at lower loads as seen in Fig. 5(b). This could be explained by the lower oxygen concentration in the blends and incomplete combustion at lower loads. Further, by increasing load the injected fuel and consequently oxygen content was increased as well as peak temperature of gas inside the cylinder and hence the higher the load the larger oxidation of the products and the lower the HC emissions. The increase of HC with the addition of DEE as well as ethanol may due to the following reasons. First was the higher heat of evaporation of the ethanol or DEE in the blends which tended to produce slow vaporization and poorer fuel-air mixing which leading to incomplete combustion of the fuel-air mixture. Another reason was the increased spray penetration causing undesired fuel impingement on the chamber walls and so flame quenching and cushioning in the ring land areas. The third was related to the so-called ‘lean flame out region’. This region was referred to a region near the outer edge of the spray in which, the mixture was often observed to be too lean to ignite or to support stable combustion. Lower temperatures and pressures extended this region and increased HC. The optimum selected blend as E10DEE8 had the lowest level of HC emission at full load condition. Sudhakar and Sivaprakasam [35] declared that HC emissions were increased for E15 by 5% as seen in Fig. 6(a). The addition of DEE at 10 and 20 percent by injection at full load condition resulted in increase of HC emissions by 8% and 22% respectively. However, HC emissions are increased marginally at initial and mid level loads due to higher heat of evaporation of ethanol into diesel caused slower the process of fuel evaporation leaded the unburned hydrocarbon increased at initial loads. When the lower heat of evaporation fuel DEE injected induced the process earlier than diesel resulted in decreases of HC at high level loads. Sudhakar and Sivaprakasam [36] declared that the increasing percentage of DEE injection resulted marginal increase in HC emission. The exhaust gas recirculation (EGR) system further increased the HC emissions marginally at low load conditions. Paul et al [37] declared that diesel-DEE blends produced lower HC emission than diesel. This reduction in HC emission might have happened because of the improved combustion condition due to the release of molecular oxygen of DEE in comparison to baseline diesel. DEE5 blend reduced the HC emissions between 30.66-40.56%, whereas DEE10 blend reduced the HC emission between 49.23-60.83% at different load conditions. This reduction was also an indication that the increasing oxygenated content of fuel helped in reduction of HC emission. Addition of ethanol to the DEE blends further reduced the HC emission as seen in Fig. 6(b). It was found that 5 and 10% ethanol addition to diesel-DEE blends reduced the HC emission in a significant manner. DEE5E5 and DEE5E10 blends produced 90.13% and 80.481% less hydrocarbon than baseline diesel, whereas DEE10E5 and DEE10E10 blends produced a maximum reduction of 84.33% and 91.12%. These decreases were due to better combustion of the charge.



(a) (b)

Fig. 6. Effect of diethyl ether additive on HC emissions of ethanol-diesel blends [35, 37]



(a) (b)

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

Patnaik et al [41] declared that HC emission was lowered with DEE15 blend by about 42% compared to that of diesel as seen in Fig. 7(a). The low boiling point and high cetane number of DEE gave an advanced start of combustion, leading to increase in combustion gas temperature at earlier stage of combustion and rapidly reached the activation temperature of carbon combustion. This improved oxidization of the hydrocarbon fuels, leading to better combustion with a reduction in HC emission. Karabektas [46] declared that the use of natural gas as a dual fuel (NG40) caused a considerable increase in the HC emissions compared with diesel fuel. One of the reasons of this increase was the escape of natural gas through the exhaust port during valve overlap. Moreover, low cylinder temperatures and pressures at particularly low engine loads deteriorated the combustion, thus yielding high HC emissions. Lower charge temperature with natural gas usage leaded to slower combustion and higher HC emissions. The use of DEE leaded to higher HC emissions in comparison to the use of NG40 as seen in Fig. 7(b). It was seen from the figure that the highest HC emissions were obtained with NG40DEE10. The increase in HC emissions with the use of DEE could be attributed to the leakage of the fuel through the injector nozzle due to the considerably low viscosity of the fuel. DEE additive had a low charge temperature and decreased combustion temperature due to its high heat of evaporation. Additionally, some of the DEE additive mixed with air during fuel injection and accumulated in the ring space between the piston and cylinder. Consequently, the combustion flame cannot effectively reach these spaces, thus yielding high HC emissions. Rakopoulos [50] declared that HC emitted by the DEE blends were higher than those of the neat biodiesel as seen in Fig. 8(a). As known, the formation of unburned hydrocarbons originated from various sources in the engine cylinder. These sources, in the present case, explaining the increased HC emissions with the DEE blends might be the increased spray life causing unwanted fuel impingement on the combustion chamber walls and so flame quenching and mainly the increase of the so called lean outer flame zone where flame was unable to exist. The latter one referred to the envelop of the spray boundary where the fuel has already mixed beyond the lean flammability limit during the ignition delay period and, thus, will not be able to auto-ignite or sustain a fast reaction front. Krishna et al [53] declared that HC emissions for the DEE blends are higher than those for pure diesel and biodiesel as seen in Fig. 8(b). HC emissions of 25% DEE blend with Karanja oil operation has been found to be 27 ppm as compared to 44 ppm of pure karanja oil and 29 ppm of pure diesel operation respectively at full load. The formation of HC emissions began from various sources in the engine cylinder, but one amongst them was the lesser quantity of oxygen available at higher loads, due to the richer fuel air mixture. Also, some of the fuel might be injected lately during the fuel injection into the combustion chamber due to late atomization, attributed to the higher viscosity of the vegetable oil blends and richer fuel air mixture then the chanced of increase in HC emissions was higher.

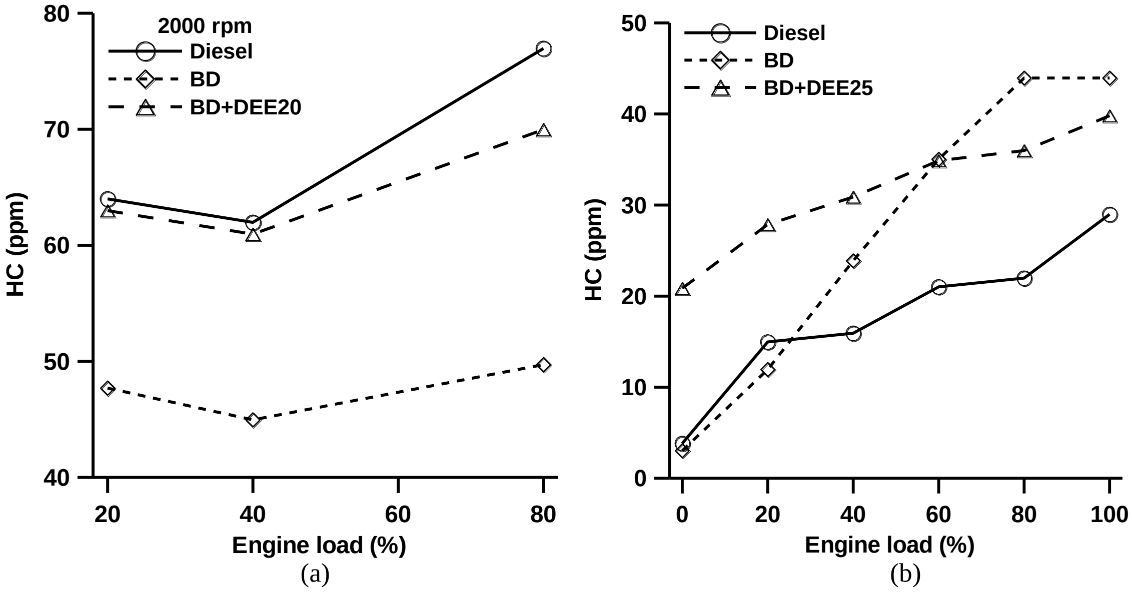


Fig. 8. Effect of diethyl ether additive on HC emissions of biodiesel [50, 53]

Sivalakshmi and Balusamy [59] declared that HC emissions for all the fuel blends were higher than biodiesel, with the increase being higher the higher the percentage of DEE in the blend as seen in Fig. 9(a). As known, the formation of unburned HC originates from various sources and varies widely with operating conditions. This could be explained as follows. Firstly, the increase of HC might be due to the higher latent heat of evaporation of diethyl ether causing lower combustion temperature, especially the temperature near the cylinder walls during the mixture formation. In this case more HC was produced from the cylinder boundary. Secondly, it might attribute the late escape into the cylinder of the fuel left in the nozzle sac volume, because with the addition of diethyl ether, this was easier to evaporate and 'slipped' into the cylinder. Rajan et al [64] declared that HC emission increased for neat biodiesel and increase of DEE in the blend with neat biodiesel at full load as seen in Fig. 9(b). The maximum HC emissions for 10% and 15% DEE were 41 and 47 ppm, whereas for diesel and neat biodiesel, these were 33 and 38 ppm, respectively, at full load. This increase in HC emission for DEE blends might be due to incomplete combustion at very high loads and low calorific value of DEE, which resulted in higher HC emissions. Also, another reason for HC emission at full load was the high latent heat of vaporization of DEE in cooling the charge at full load conditions.

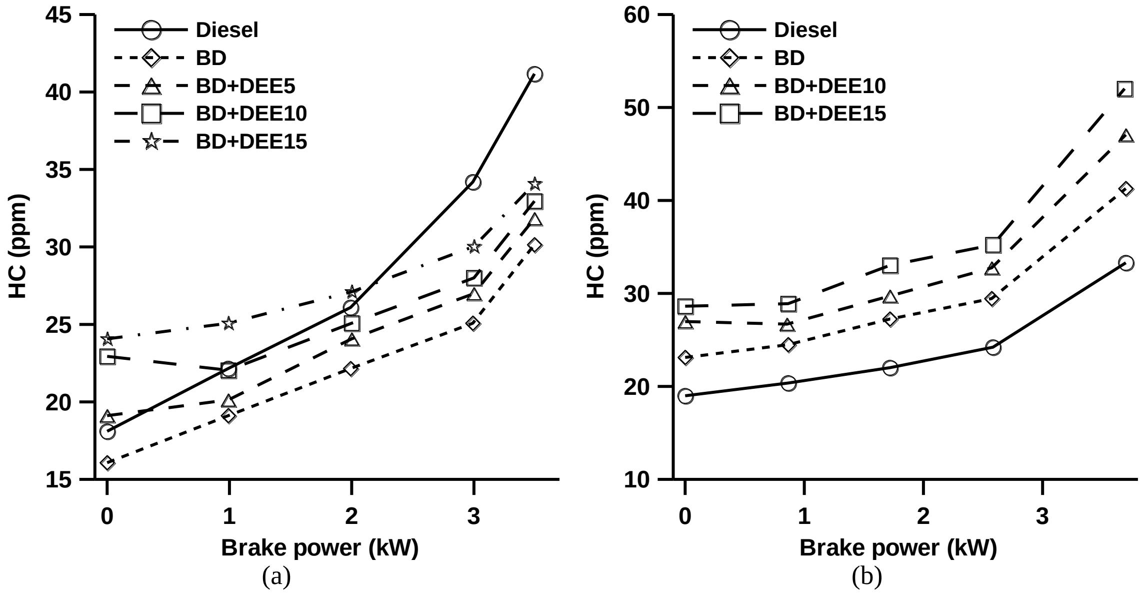
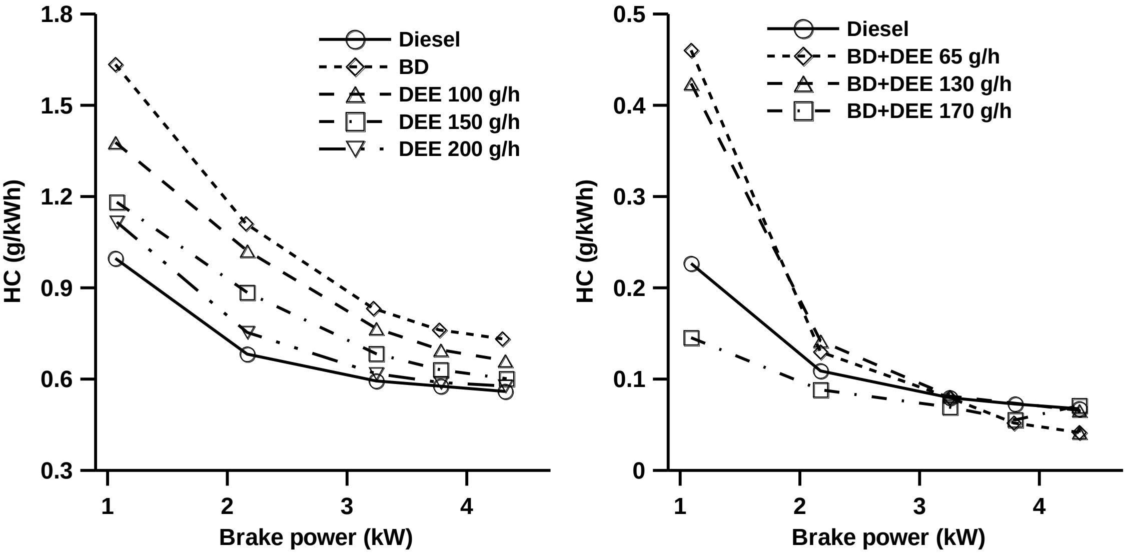


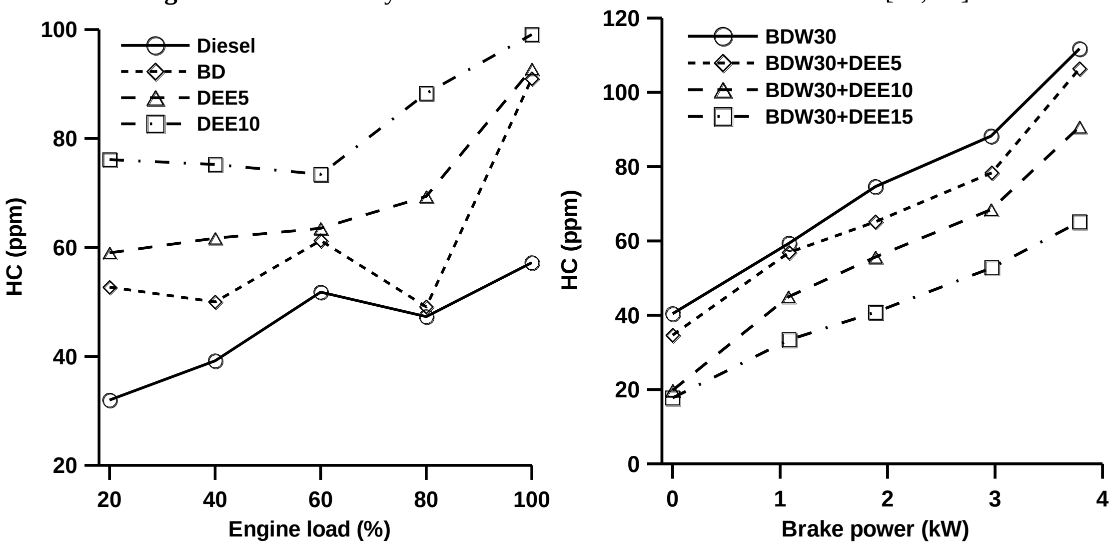
Fig. 9. Effect of diethyl ether additive on HC emissions of biodiesel [59, 64]

Geo et al [65] declared that the HC concentration for biodiesel operation showed higher value at all loads in comparison with diesel fuel operation as seen Fig. 10(a). With biodiesel operation HC concentration ranged from 1.6 g/kWh at 25% load to 0.7 g/kWh at 100% load whereas with diesel it ranges from 1 g/kWh to 0.5 g/kWh. This was mainly due to the higher density and viscosity of biodiesel which caused poor mixture formation resulting in partially burned hydrocarbons (incomplete combustion) during combustion process. DEE admission with biodiesel reduced the HC emissions. With 200 g/h of DEE, HC emission varies from 1.1 g/kWh to 0.6 g/kWh. The presence of oxygen and better mixing of DEE with air leaded to improved combustion rate. Also, the oxygen was more in the combustion process, which increased the efficiency of the oxidation of hydrocarbons in the fuel resulting in reduced hydrocarbons. Hariharan et al [66] declared that biodiesel-DEE operation showed higher values of hydrocarbon emission over the entire range of operation in particular at low loads compared to that of diesel operation as seen in Fig. 10(b). For diesel fuel, HC emission varied from 0.23 g/kWh at low load to 0.06 g/kWh at full load. While operating with biodiesel-DEE at 130 g/h, HC varied from 0.4 g/kWh at low load to 0.07 g/kWh at full load, from 0.5 g/kW h at low load to 0.04 g/kWh at full load with 65 g/h flow rate and from 0.4 g/kWh at low load to 0.05 g/kWh at full load with 170 g/h flow rate. At low loads, the unburnt hydrocarbon (UHC) emission was very high. This might be attributed to the higher quantity of DEE introduced along with intake air in the form of premixed charge. This premixed charge would occupy the crevice volume where the flames would not propagate. In addition the temperature prevailing inside the cylinder at that instance was low. At low loads, the high boiling compounds present in biodiesel might had less chance to breakdown and hence resulted in more HC up to part load operation. Poor mixture formation and lower air entrainment of biodiesel were also the reasons for higher HC emission in biodiesel-DEE operation.



(a) (b)

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

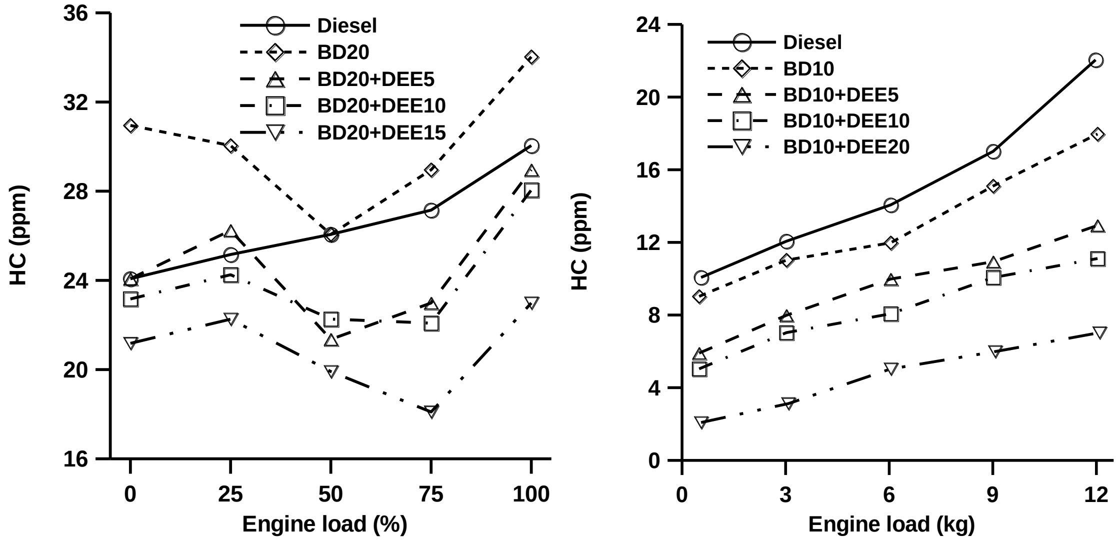


(a) (b)

Fig. 11. Effect of diethyl ether additive on HC emissions of biodiesel [67] and biodiesel-water emulsified fuel [70]

Devaraj et al [67] declared that the addition of DEE with biodiesel increased the HC emissions than diesel as seen in Fig. 11(a). The reason behind increased HC in biodiesel might be due to higher fumigation rate. The increase in HC emissions with the use of DEE10 could be attributed to the leakage of the fuel through the injector nozzle due to the considerably low viscosity of DEE. DEE additive had a low charge temperature and decreased combustion temperature due to its high heat of evaporation. Additionally, some of the DEE additive mixed with air during fuel injection and accumulated in the ring space between the piston and cylinder. Consequently, the combustion flame could not effectively reach these spaces, thus yielding high HC emissions. Sachuthananthan and Jeyachandran

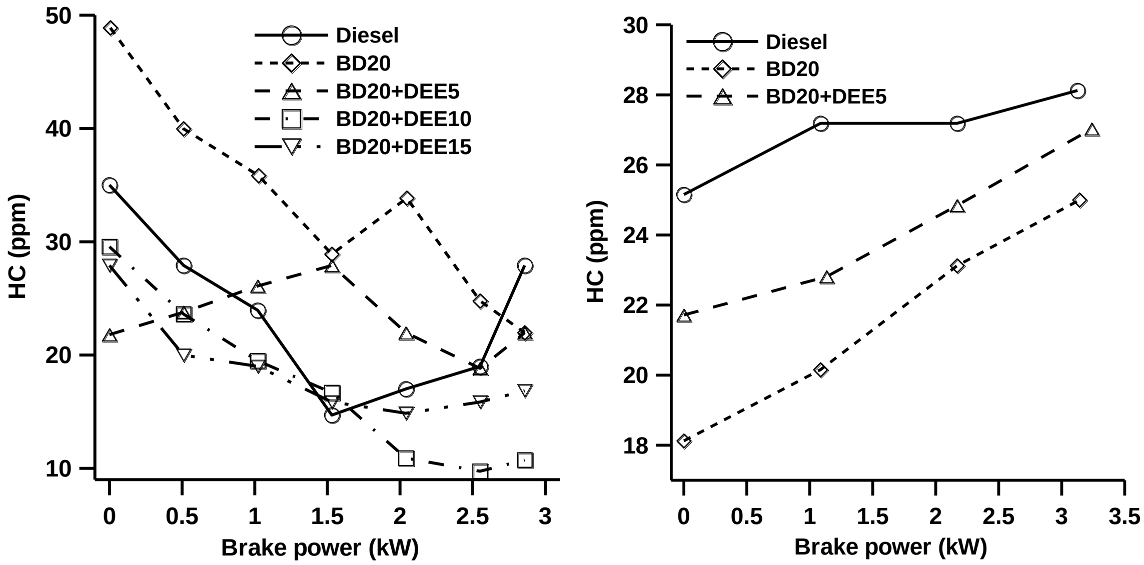
[70] declared that with neat 30% water biodiesel emulsion HC emission was 112ppm at full load and for 5% DEE addition it reduced to 106ppm and for 10% DEE the HC emission further reduced to 91ppm and for 15% DEE it was only 65ppm at full load condition as seen in Fig. 11(b). This was because as DEE was an oxygenated compound containing 21.6% of oxygen by mass reduced the ignition delay and the effect of water on combustion process reduced, and hence the combustion became more complete and the HC emission reduced. Kumar et al [74] declared that HC emission increased for neat BD20 and it decreased with adding DEE in the BD20 at all load conditions as seen in Fig. 12(a). The percentage increases of HC with respect to diesel and BD20 was 13.33% and percentage decreases of HC with respect to BD20 and BD20DEE15 was 32.35%. This decrease in HC emission for DEE blends due to improper combustion. Ganesha and Chethan [75] declared that HC emission increased with changing load by observing Fig. 12(b). Diesel has maximum HC emission in all load compared with all biodiesel-diesel and DEE blends. Minimum emission is obtained for blend BD10DEE20. Because of biodiesel poor atomizing characteristic is improvising due to DEE properties of reduction in viscosity so that proper combustion results in less unburned HC emission. HC emission for diesel has maximum at all load is 10,12,14,17 and 22 ppm respectively. Minimum emission occurs for BD10DEE20 is 2, 3, 5, 6 and 7 ppm respectively.



(a) (b)

Fig. 12. Effect of diethyl ether additive on HC emissions of biodiesel-diesel blends [74, 75]

Srihari et al [76] declared that HC emissions were much higher for BD20 blend than that of diesel fuel for all loads as seen in Fig. 13(a). DEE5 blend has not given a discernible improvement in HC emissions with that of diesel fuel. However, DEE10 and DEE15 are worth considering as the HC emissions are fairly low in the two cases when compared to that of diesel fuel. This could be due to the addition of DEE which tends to support the combustion process. Here the fuel bound oxygen oxidizes the HC molecules converting them into H_2O and CO_2 and thus facilitating complete combustion. A reduction of 15% and 40% has been achieved on an average with DEE15 blend when compared to that of diesel and BD20 respectively. Abraham and Thomas [79] declared that HC emissions decreased with increase in blend proportion at a constant load. HC emission of the BD20 and DEE5 blends is less than that of diesel fuel as seen in Fig. 13(b) due to inherent presence of oxygen in the molecular structure of the biodiesel and DEE.



(a) (b)

Fig. 13. Effect of diethyl ether additive on HC emissions of biodiesel-diesel blends [76, 79]

Fig. 14(a) shows the comparative results of hydrocarbons obtained with different blends and BD. It can be noticed that BD20 with smaller amounts of DEE yielded lower hydrocarbons in the exhaust. This is due to the fact that DEE has enhanced the combustion process. The hydrocarbons in case of BD are far higher than DEE5 blend with BD20 [81]. It is observed from Fig. 14(b) that HC emission is increased for BD20 and it is also increased with increase of DEE in BD20 blend. The maximum HC emissions for DEE10 and DEE15 are 47ppm and 40ppm, whereas for diesel and BD20 are 33ppm and 38ppm respectively at full load. This increase in HC emission for DEE blends may be is due to incomplete combustion at very high loads and low calorific value of DEE which results in higher HC emissions. Also the another reason for HC emission at full load is the high latent heat of vaporization of DEE results in cooling the charge at full load conditions [83].

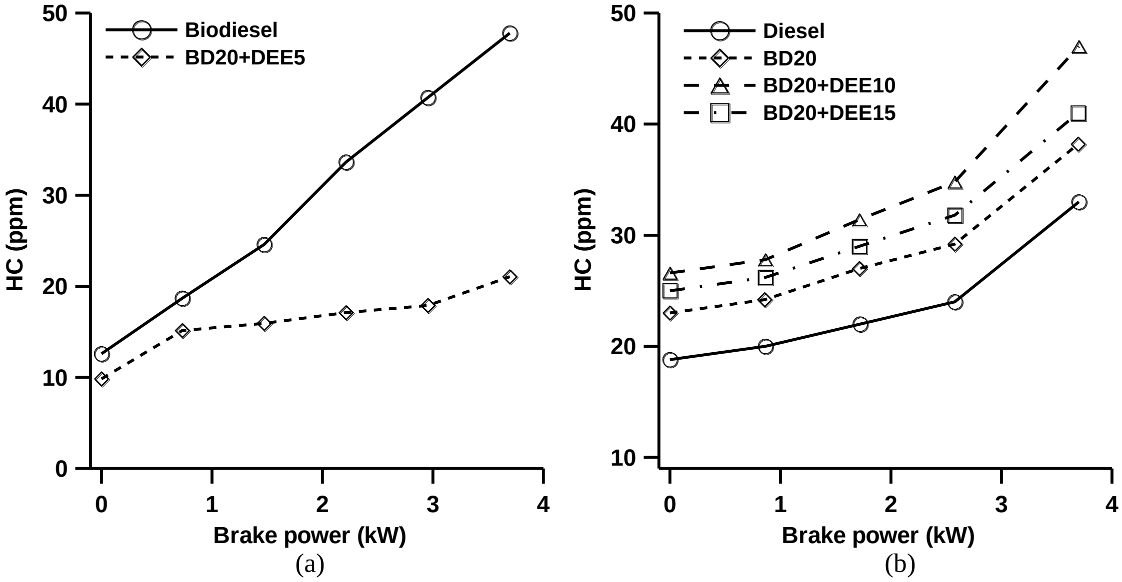


Fig. 14. Effect of diethyl ether additive on HC emissions of biodiesel-diesel blends [81, 83]

HC emission for the test fuels with different engine speeds are shown in Fig. 15(a). There are number of reasons for the HC emission during combustion. Fuel trapping in the crevice volumes of the combustion chamber is one of the major reasons of HC emission. Locally over-lean or over-rich mixture, incomplete fuel evaporation and liquid wall films for excessive spray impingement are also having been mentioned as significant factors. It can be seen from the figure that BD20 gave significantly lower HC than diesel fuel all over the engine speed range. It gave about 28% decreased emission than diesel on average. Such decrement can be attributed to the higher oxygen content of biodiesel which influenced the amount of hydrocarbon oxidation. On the contrary, BD15DEE5 and BD10DEE10 showed 32% and 52% increment. HC emission was supposed to be reduced due to even higher oxygen content of DEE. However, slip of fuel out of the cylinder especially at low speed during expansion stroke might be the reason for such higher emission as additives like DEE made fuel evaporation easier. Hence, IDI diesel engine inherently creates a homogeneous charge, consequently, addition of DEE may create lean outer flame zone. This is actually the envelope of the spray boundary where because of over-mixing the fuel is already beyond the flammability limit [91].

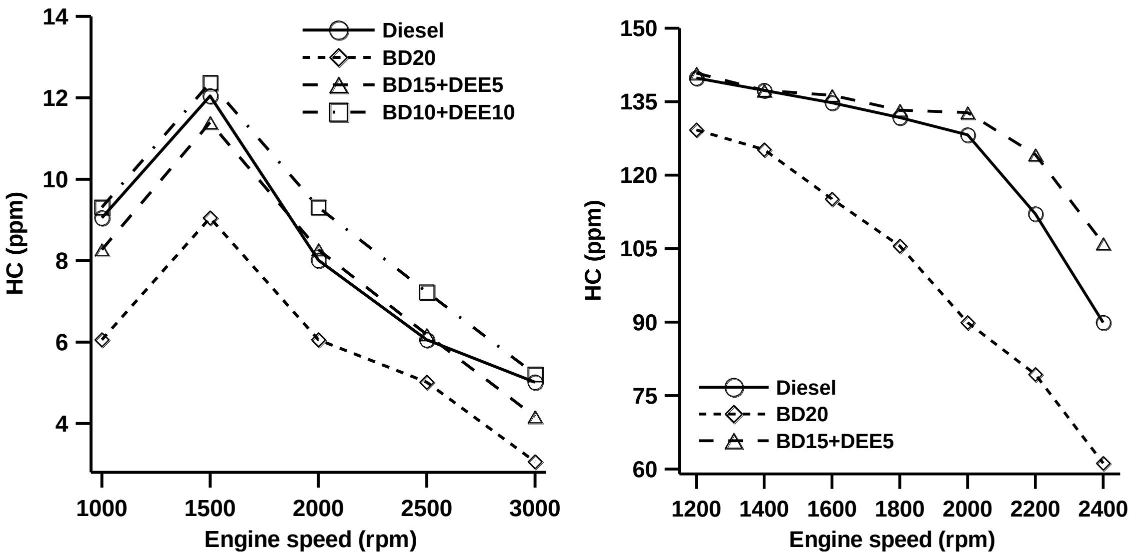


Fig. 15. Effect of diethyl ether additive on HC emissions of biodiesel-diesel blends [91, 98]

The effect of additives on HC emission is shown in the Fig. 15(b). Unburned hydrocarbon originates from various sources in the cylinder during combustion. It can be observed that, oxygenated compounds available in the biodiesel made the HC emission lower in the case of BD20. In spite of higher oxygen content of diethyl ether, DEE5 blend showed higher amounts of HC emission. This behavior can be the effect of addition of additives like ethanol and diethyl ether which make it easier to evaporate the fuel and slipped into the cylinder especially at low speed during expansion stroke. Another reason can be mentioned here is the increase of ‘lean outer flame zone'. This actually means the envelope of the spray boundary where the fuel is already beyond the flammability limit because of over mixing [98]. HC trend of tested fuels is shown in Fig. 16(a). Incomplete/partial combustion of fuel inside the engine cylinder leads to the formation of HC. It is obvious that the HC emissions are higher for the biodiesel blend in comparison with diesel at all loading conditions. Hydrocarbon emission increases with increase in engine load for all the tested fuels due to more quantity of fuel being injected. HC emission is greatly influenced by the nature of combustion and this value is a minimal for complete combustion. The biodiesel have more oxygen content compared to diesel and hence it is expected that the HC emissions for biodiesel should be less than neat diesel. This is because higher oxygen content may lead to better combustion. But, HC emissions increases with biodiesel and this is because even though the oxygen content is more, the kinematic viscosity of all the biodiesel blends are higher than neat diesel. DEE15 blend has minimum HC emissions and this is because the addition of DEE increases the cetane index of the blend resulting in comparatively complete combustion [102].

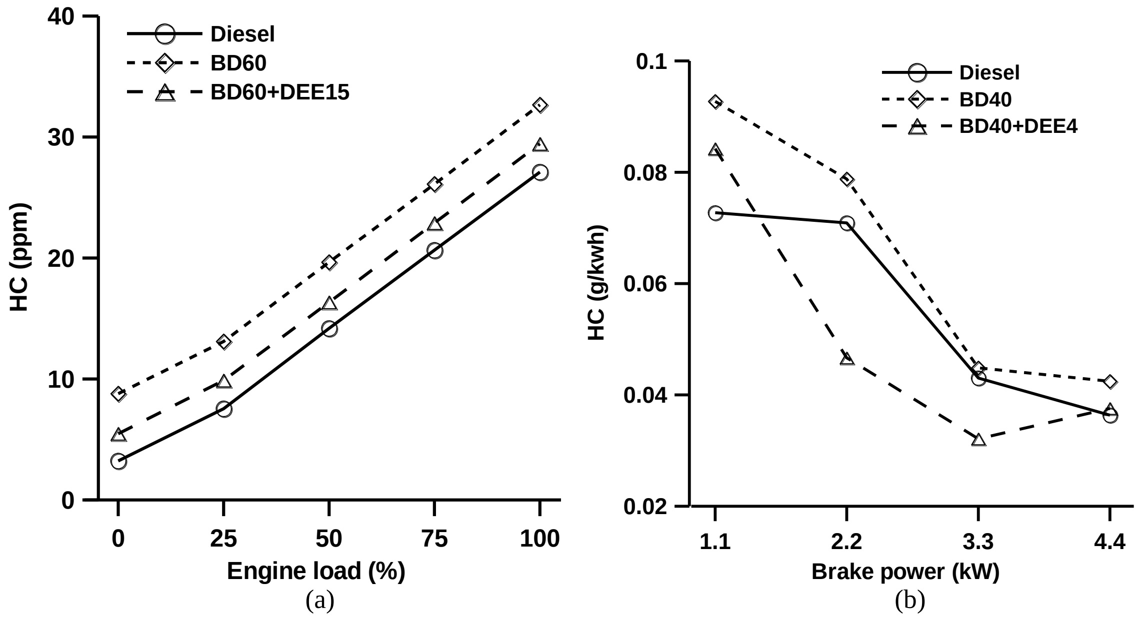


Fig. 16. Effect of diethyl ether additive on HC emissions of biodiesel-diesel blends [102, 107]

The HC emission of the diesel engine is primarily influenced by the fuel quality and the oxygen available for complete combustion. It is also influenced by the ignition delay and rate of reaction and engine design. The variation of HC emission with brake power is illustrated in Fig. 16(b). It can be observed from the figure that BD40 operation exhibits higher HC emission than that of the diesel operation. The higher aromatic content and poor mixture formation may be the reasons for the higher HC emission. HC concentration for DEE4 blend is lower compared to BD40 blend and diesel fuel. The reason may be the addition of DEE which provides oxygen for improved oxidation. HC emission of DEE4 is about 14% lower compared to that of BD40 blend [107]. Fig. 17 illustrates the variation of HC with respect to brake power for various test fuels. DEE5 and DEE10 exhibit higher HC during high engine load, in comparison with BD40E20. Higher latent heat of evaporation of DEE mixture promotes lower temperature combustion (LTC) during the combustion, thereby resulting in more fuel accumulation during the premixed combustion phase which is predominant in engine combustion chamber walls. The temperature near the cylinder walls during the mixture formation influences the HC formation especially at cylinder boundary. This causes more unburned hydrocarbon formation for DEE blends at high load [110].

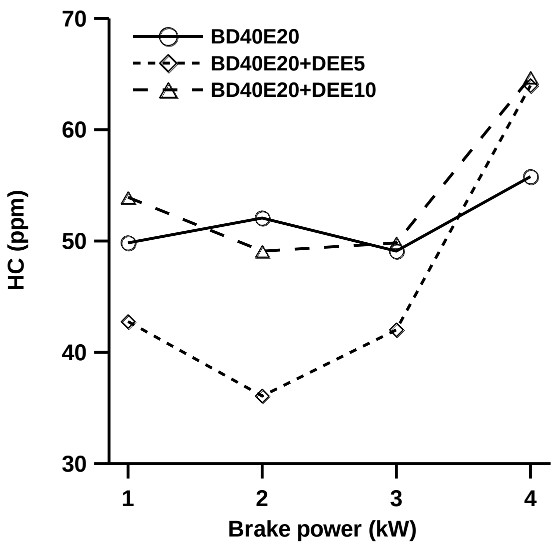


Fig 17. Effect of diethyl ether additive on HC emissions of biodiesel-ethanol blend [110]

Numerical values about diethyl ether addition on HC emissions are tabulated in Table 2. The suitable values with the variations in the presented figures can be seen in Table 2 with ethyl ether addition into various diesel engine fuels.

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

Base fuel + Additive	HC emissions (variation %)	Ref.
D + 24% DEE	↑ 32.5-37.4	[17]
D + 20% DEE	↓ 31.5-56.5	[22]
D + 50% DEE	↓ 11.4-37.4	[23]
D + 10% DEE	↓ 2.7-6.9	[29]
D + 15% BD + 5% DEE	↓ 0.9-18.2	[31]
D + 30% DEE	↑ 46.2	[32]
D + 10% E + 15% DEE	↑ 71.7-125.2	[33]
D + 15% E + 30% DEE	↑ 21.7-257.8	[35]
D + 10% E + 10% DEE	↓ 21.1-91.5	[37]
D + 15% DEE	↓ 10.4-31.8	[41]
D + 40% NG + 10% DEE	↑ 795-1636	[46]
BD + 20% DEE	↓ 1.5-9.1	[50]
BD + 25% DEE	↑ 37.3-445.8	[53]
BD + 15% DEE	↓ 17.2 ↑ 32.9	[59]
BD + 15% DEE	↑ 41.9-56.2	[64]
BD + 200 g/h DEE	↑ 2.1-11.9	[65]
BD + 170 g/h DEE	↓ 35.8 ↑ 5.1	[66]
BD + 10% DEE	↑ 41.7-138	[67]
BD + 30% W + 15% DEE	↓ 40.2-56.1	[70]
D + 20% BD + 15% DEE	↓ 11.5-33.3	[74]
D + 10% BD + 20% DEE	↓ 64.2-79.3	[75]
D + 20% BD + 15% DEE	↓ 39.6 ↑ 7.8	[76]
D + 20% BD + 5% DEE	↓ 3.9-16.1	[79]
D + 20% BD + 5% DEE	↓ 18.9-56	[81]
D + 20% BD + 15% DEE	↑ 24.2-32.9	[83]
D + 10% BD + 10% DEE	↑ 2.8-19.3	[91]
D + 15% BD + 5% DEE	↑ 0.7-17.9	[98]
D + 60% BD + 15% DEE	↑ 8.6-69.6	[102]
D + 40% BD + 4% DEE	↓ 34.2 ↑ 15.8	[107]
D + 40% BD + 20% E + 10% DEE	↓ 5.7 ↑ 16	[110]

5. Conclusions

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

- HC is partially burned and unburned fuel emission. The HC emission of the diesel engine is primarily influenced by the fuel quality and the oxygen available for complete combustion. It is also influenced by the ignition delay and rate of reaction and engine design.
- There are number of reasons for the HC emission during combustion. Fuel trapping in the crevice volumes of the combustion chamber is one of the major reasons of HC emission. Locally over-lean or over-rich mixture, incomplete fuel evaporation and liquid wall films for excessive spray impingement are also significant factors.
- Low cylinder temperatures and pressures at particularly low engine loads deteriorated the combustion, thus yielding high HC emissions. Over-leaning of fuel injected during the ignition delay period is a significant source of hydrocarbon emissions especially when the ignition delay is long. During the compression period, the premixed fuel charge trapped in the cylinder crevices influenced the increase in HC emissions.
- DEE exhibits a shorter ignition delay period than diesel due to the better autoignitability of DEE, leading to increase in combustion gas temperature at earlier stage of combustion and rapidly reached the activation temperature of combustion. This improved oxidization of the hydrocarbon fuels, leading to better combustion with a reduction in HC emission. Another reason for low HC by DEE blends is that the higher oxygen content in the blends helps to combust the unburned fuel in the combustion chamber during the diffusion flame phase.

- The higher density and viscosity of biodiesel causes poor mixture formation and results in partially burned hydrocarbons during combustion process. The higher aromatic content and poor mixture formation are the reasons for the higher HC emission for biodiesel fuels. The presence of oxygen which increased the efficiency of the oxidation of hydrocarbons in the fuel and better mixing of DEE with air leads to improved combustion. Thus, DEE addition into biodiesel reduces the HC emissions.
- In spite of higher oxygen content of diethyl ether, DEE blends can show higher amounts of HC emission. The higher heat of vaporization of DEE produces slow vaporization and poorer fuel-air mixing which leading to incomplete combustion. Another reason is the increased spray penetration causing undesired fuel impingement on the chamber walls and so flame quenching and cushioning in the ring land areas. The third is related to the so-called ‘lean flame out region’. This region is referred to a region near the outer edge of the spray in which, the mixture is often observed to be too lean to ignite or to support stable combustion. Lower temperatures and pressures extend this region and increased HC.

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
DMC : Dimethyl carbonate
DME : Dimethyl ether
E : Ethanol
EGR : Exhaust gas recirculation
HCCI : Homogenous charge compression ignition
MTBE : Methyl tertiary butyl ether
NG : Natural gas
NOx : Nitrogen oxides
PCCI : Partially charge compression ignition
PM : Particulate matter
SOx : Sulphur oxides
W : Water

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