Performance and Emission Characteristics of Diesel Engine Fuelled with Biodiesel and its Blends: A Review

B.M.Gitte [1], Sayyed Siraj [2], H.M. Dharmadhikari [3]
[1, 2, 3] *Dept. of Mechanical Engineering, Maharashtra Institute of Technology, Aurangabad*

Abstract

Depleting reserves, growing prices of crude oil, stringent emission norms and greenhouse gas concerns have led to an ever increasing effort to develop alternative fuel sources, with particular emphasis on bio fuels that possess the added benefit of being renewable. In this regard biodiesel has emerged as a very promising solution. The article is a literature review of the effects of biodiesel fuel and its blends on performance and emission characteristics of compression ignition engine. The literature regarding the effect of biodiesel fuel and its blends on engine brake power, fuel consumption and thermal efficiency are collected and analyzed with that of conventional diesel fuel. The engine emissions from biodiesel and diesel fuels are compared. The study is based on the reports of scientists who published their findings between 2005 and 2012. The scientists and researchers conducted the test, using different types of feedstock biodiesels and their blends with diesel. It was reported that there was a slight decrease in brake power and a slight increase in fuel consumption. However, the lubricant properties of the biodiesel are better than diesel, which can help to increase the engine life. The biodiesel fuel is environment friendly, produces much less CO and HC and absolutely no SO_2 and no increase in CO_2 at global level.

Key words: *Biodiesel; Biodiesel blends; diesel engine; performance; emission.*

1. Introduction

Energy is one of the most important resources for mankind and its sustainable development. Today, the energy crisis becomes one of the global issues confronting us. Fuels are of great importance because they can be burned to produce significant amounts of energy. Many aspects of everyday life rely on fuels, in particular the transport of goods and people. Most industries use machines for the production process with diesel engine prime movers. In the transportation sector, private vehicles, buses, trucks, and ships also consume significant amounts of diesel and gasoline. Main energy resources come from fossil fuels such as petrol oil, coal and natural gas. Fossil fuel contributes 80% of the world's energy needs. This situation leads to a strong dependence of everyday life on fossil fuels. However, the energy demand due to the population growth is not covered by domestic crude oil production [1]. Fossil oils are fuels which come from ancient animals and microorganisms. Fossil fuel formation requires millions of years. Thus, fossil oils belong to non-renewable energy sources. An increase of the oil price often leads to economic recessions, as well as global and international conflicts [2-3].

Energy security is a key ingredient for the economic stability of every country, particularly for those that do not have adequate fossil or nuclear resources. In this regard, depleting reserves and rising prices of crude oil, having placed negative loads on the trade balances of the non-oil producing countries, are posing a severe threat to the world economy since petroleum prices form the basis of the world industrialization. These facts, coupled with the continuously growing concern over global warming and environmental degradation in general (e.g. acid rain, smog, climate changes), have accentuated the public and scientific awareness and led to a substantial effort to develop alternative fuel sources. Among those, bio fuels have assumed a leading role since they possess the critical benefit of being renewable [4].

The term bio fuel refers to any fuel that is derived from biomass, such as sugars, vegetable oils, animal fats, etc. Bio fuels made from agricultural products reduce the countries' dependence on oil imports, support local agricultural industries and enhance farming incomes, while offering benefits in terms of sustainability and reduced particulate matter emissions. Since the carbon in the biodiesel originated mostly from CO_2 in the air, the full cycle CO_2 emissions for biodiesel contribute much less to global warming than fossil fuels. What is equally important, from an economic point of view, is that they are more evenly distributed than fossil or nuclear resources, since they can be produced domestically. Consequently, they constitute a long-term measure to, at least in part, increase energy security and diversity. Among the bio fuels currently in use or under consideration, biodiesel (methyl or ethyl ester) is considered as a very promising fuel for the transportation sector since it possesses similar properties with diesel fuel, it is miscible with diesel practically at any proportion, and is compatible with the existing distribution infrastructure. Moreover, biodiesel is less toxic than petro diesel and is also biodegradable. It has superior emission characteristics [5-6].

Biodiesel is produced by transesterification of vegetable oils, animal fats or recycled cooking oils, and consists of long-chain alkyl esters, which contain two oxygen atoms per molecule. The most widely used biodiesels are rapeseed methyl ester (RME) in Europe and soybean methyl ester (SME) in the US; other popular biodiesels are jatropha, karanja, palm, sunflower, cottonseed, waste cooking and tallow methyl esters, collectively known as fatty acid methyl esters (FAME) [7].

In India widely used biodiesels are jatropha and karanja methyl esters. The Government of India had launched the National Bio-diesel Mission (NBM) after identifying jatropha (Jatropha curcas) as the most suitable tree borne non edible oilseed for biodiesel production. The central government and several state governments provide fiscal incentives in support of planting jatropha and other inedible oilseeds.

Nomenclature

B100	neat biodiesel	FAME	fatty acid methyl ester
BSFC	brake specific fuel consumption	LHV	lower heating value
BTE	brake thermal efficiency	NO_X	Nitrogen oxides
CO	carbon monoxide	PME	palm methyl ester
CO_2	carbon dioxide	PPO	pure plant oil
DF	diesel fuel	RSO	rapeseed oil
DI	direct injection	SME	soybean methyl ester
EGR	exhaust gas recirculation	THC	total hydrocarbon

2. Properties of biodiesel

The Properties of biodiesel are close to mineral diesel. Therefore, biodiesel becomes a strong alternative to replace the mineral diesel. The attractive characteristics of biodiesel include higher cetane number, non-toxic emissions, and bio-degradability, absence of sulphur and aromatic compounds and excellent lubricity. The properties of some of the biodiesel fuels of different originating oils are compared in Table 1. Biodiesel has viscosity higher than mineral diesel. These vegetable oil esters contain 10–11% oxygen by weight, which may encourage combustion than hydrocarbon-based diesel in an engine. Its cloud point and pour point are 15–25 ^{0}C higher than those of mineral diesel [3, 4, 10, 13].

Cetane number represents the ignitability of the fuel, particularly critical during cold starting conditions. Higher cetane number leads shorter ignition delay. Higher cetane numbers promote faster auto-ignition of the fuel, and often lead to lower NOx emissions. Cetane numbers of the originating oils range from 50.4 for rubber seed methyl ester to 61.2 for PME, with the mean value from all feedstock's being 54.8; that is 8-10% higher than that of petro diesel.

Biodiesel fuels are characterized by higher density than conventional petroleum diesel, which means that volumetrically operating fuel pumps will inject greater mass of biodiesel than conventional diesel fuel. This in turn will affect the air fuel ratio hence the local gas temperatures and NOx emissions, as long as the engine retains its diesel-fuel calibration. The (average) densities of the methyl esters range from 870.8 to 891.5 kg/m^3, with the overall average value being 880.2 kg/m^3 i.e. almost 5% higher than the corresponding petro diesel value.

Heating value of a fuel is a measure of a fuel's heat of combustion. Oxygen content of biodiesel leads to proportionally lower energy density and heating value, thus more fuel needs to be injected in order to achieve the same engine power output. Methyl esters exhibit LHV from 35,990 to 38,800 kJ/kg with an average value of 37,610 kJ/kg; this is 10-11% lower than the corresponding mineral diesel fuel's LHV.

Viscosity is a measure of the resistance of a fluid which is being deformed by either shear or tensile stress. In case of liquid fuels, the less viscous the fluid is, the greater its ease of movement (fluidity). In a diesel engine, higher viscosity leads to less accurate operation of the fuel injectors, and to poorer atomization of the fuel spray. Vegetable oils have high viscosity. The transesterification process considerably reduces the viscosity of the FAME to levels comparable to that of petro diesel, but still higher. The kinematic viscosity values of the FAME range from 2.78 mm^2/s to 5.06 mm^2/s, with the mean value from all feedstock's being 4.55mm^2/s.

The flash point is a measure of the temperature to which a fuel must be heated such that the mixture of vapour and air above the fuel can be ignited. The flash varies inversely with the fuel's volatility. Storage of neat biodiesel is thus much safer than diesel in this regard. The average values of flash point for biodiesels range from 127.7 ^{0}C to 174.5 ^{0}C with the mean value from all feedstock's being 163.3 ^{0}C.

Table 1
Properties of biodiesels of different originating oil [3, 4, 10]

	Cetane number	Density (kg/m^3)	LHV (kJ/kg)	Viscosity (mm^2/s)	Flash point (^{0}C)	Pour point (^{0}C)	Cloud point (^{0}C)
Diesel	47.0	834.0	42588	2.83	62.0	-16	2.0
Cottonseed	53.3	879.0	38,175	4.70	165.4	-0.2	1.2
Jatropha	55.7	878.7	38,050	4.72	158.5	-0.9	5.7
Karanja	55.4	882.9	36,490	5.04	163.6	2.5	7.6
Neem	54.2	876.2	37,155	4.72	162.5	6.1	11.6
Palm	61.2	874.7	37,080	4.61	161.9	11.8	13.3
Rapeseed	50.4	882.3	37,820	4.79	158.3	-7.0	3.6
Soybean	51.8	882.8	37,750	4.29	158.8	-3.0	0.1
Sunflower	51.9	882.9	37,800	4.53	172.0	-3.8	0.9
Coconut	61.0	870.8	35,985	2.78	127.7	-3.8	-1.2
Mahua	56.9	874.5	36,880	5.06	150.6	4.0	4.0
Peanut	54.9	882.9	38,050	4.77	174.5	-2.7	4.3
Waste cooking	56.2	880.6	37,880	4.75	161.7	-0.3	5.3
Rubber seed	50.4	882.3	37,820	4.79	158.3	-7.0	3.6

3. Overview of test engine and Biodiesel Blends

Numbers of researchers have published their findings on bio diesel as an alternative for compression ignition engine in last decade. Some of them have investigated the effect of biodiesel fuel on performance and emission characteristics of diesel engine. Table 2 provides a list of the published papers in international Journals and well established Conferences which deal with performance and emission characteristics of diesel engine fuelled with biodiesel and its blends. The researchers have performed the study on four stroke single cylinder / multicylinder naturally aspirated, water cooled, direct injection diesel engine. They used biodiesel and its blends of different originating oils.

Table 2
Overview of details of engine tested, Biodiesel originating oil and its Blends

Researchers	Ref.	Originating oil	Biodiesel /Blends	Engine Tested	Performance parameters	Emissions
D.H. Qi et al.	6	Soybean	B30, B5E25	1-Cylinder, 4S, NA, WC, DI	BSFC	CO, CO_2, NO_X
A.M. Liaquat et al.	13	Jatropha, waste Cooking	JB5, JB10, J5W5	1-Cylinder, 4S, NA, WC, DI	BT, BP, BSFC, BTE	HC, CO, CO_2, NO_X
Huseyin Aydin et al.	14	Sunflower	B20, BE20	1- Cylinder, 4S, DI.	BT, BP, BSFC, BTE	CO, CO_2, NO_X
H. An et al.	15	Waste cooking	B10, B20, B50 & B100	4- Cylinder, 4S, DI.	BT, BP, BSFC, BTE	HC, CO, CO_2, NO_X
L. Labecki et al.	17	Rapeseed	10%, 20%, 30% and 50% RSO	4- Cylinder, 4S, DI.	_	THC, CO, CO_2,NO_X
B.K. Highina et al.	20	Peanut	B100	2-Cylinder, 4S, NA, WC, DI	BT, BP, BSFC, BTE	_
Breda Kegl	24	Rapeseed	B100	6- Cylinder, 4S, Inline, WC, DI.	BP, BSFC, Injection pressure & Timing	HC, CO, NO_X
Ma Zhihao et al.	27	Pistacia Chinensis Bunge	B10, B20, B30	3-Cylinder, 4S, NA, WC, DI	_	HC, CO, NO_X
Su Han Park	28	Soybean	B5, B10, B20.	1- Cylinder, 4S, DI.	Ignition delay, ISFC, IMEP.	HC, CO, NO_X

4. Engine performance

4.1 Engine brake power

Most of the researchers reported the drop in engine brake power with biodiesel fuel due to its lower heating value [6-12]. However, the results reported show some variations. Some authors found that the brake power loss was lower than the expected (the loss of heating value of biodiesel compared to diesel) because of brake power recovery. A.M. Liaquat et al. [13] observed average brake power reduction of 0.67%, 1.66% and 1.54% for JB5, JB10 and J5W5 respectively over the entire speed compared to diesel fuel. The torque reduction values observed were in the same trend due to the lower heating value of blends. Huseyin Aydin et al. [14] reported the same trend with the observation that higher values of viscosity, density and cetane number being the main reason for preventing surplus brake power reduction. H. An et al. [15] found the reduction in brake power of 1.9%, 4.0% and 12.2% for B20, B50 and B100 respectively compared to diesel mainly due to the lower calorific values of biodiesel and blend fuels, except for B10 where a slight improvement was observed. Agarwal A.K [2] reported that biodiesel has a 10% lower heating value than diesel.

Based on analysis, the use of biodiesel will lead to the reduced engine brake power, which can be accepted commonly. Engine brake power will decrease with the increase of content of biodiesel [13-15]. The main reason for brake power loss is based on the reduced heating value of biodiesel compared to diesel, this viewpoint is agreed comprehensively. The high viscosity and high lubricity of biodiesel also have certain effects on engine brake power, but there is no unanimous conclusion. In addition, it seems that feedstock of biodiesel is not an important factor which affects engine brake power. In the case of no modification to an engine, the injection feature of biodiesel is influential to engine brake power. It is necessary to further research the relationship between injection pressure and injection timing and engine brake power in order to obtain the optimal match when using biodiesel.

4.2 Brake specific fuel consumption.

Most of researches [13, 14, 15,19] agreed that the fuel consumption of an engine fuelled with biodiesel becomes higher because it is needed to compensate the loss of heating value of biodiesel. Some authors [4, 7] presented that the increase in fuel consumption is basically similar to the loss of heating value for biodiesel compared to diesel. A.M. Liaquat et al. [13] observed an average increase in BSFC compared to DF as 0.54%, 1.0% and 1.14% for JB5, JB10 and J5W5 respectively, over the entire speed range. The lower heating values and higher densities of those fuels require larger mass fuel flows for the same energy output from the engine, leading to the increase of the brake specific fuel consumption to compensate the reduced chemical energy in the fuel. However, they observed that at some lower engine speeds for blend fuels, the BSFC values were lower than that of DF. The reason for lower fuel consumption for blend fuels may be because of the improved combustion due to the inherently oxygen containing**.** Huseyin Aydin et al. [14] observed average brake-specific fuel consumption for usage of B20 was 22.32% higher than that of diesel fuel

H. An et al. [15] reported that the BSFC increases with the biodiesel blend ratio, and the average increase in BSFC over all engine speeds were 2.1%, 1.5%, 3.5% and 9.6% for B10, B20, B50 and B100 respectively. They conducted the study on four strokes, DI, water cooled engine with waste cooking oil biodiesel blends. The results obtained are shown in Fig. 1 which represents the BSFC of the test engine while running with diesel, B10, B20, B50 and B100 fuels at full load conditions. The calorific value of biodiesel is reduced by 12.7% compared to diesel which is larger than the amount of increase in BSFC. This is due to the benefit of oxygenated nature of biodiesel which leads to a more complete combustion, and hence lowers the increase in BSFC.

The majority of authors agreed that fuel consumption increase when using biodiesel, but this trend will be weakened as the proportion of biodiesel reduces in the blend fuel with diesel. The increase in biodiesel fuel consumption is mainly due to its low heating value, as well as its high density and high viscosity. The different feedstock of biodiesel with different heating value and carbon chain length, or different production processes and quality, also have an impact on engine economy**.**

4.3 Brake thermal efficiency

BTE indicates the ability of the combustion system to accept the experimental fuel, and provides comparable means of assessing how efficient the energy in the fuel is converted to mechanical output. Most of the researchers found the drop in engine brake thermal efficiency with biodiesel fuel compared to diesel. The presence of oxygen molecule in the biodiesel lowers the calorific value and hence the reduction in brake thermal efficiency of the biodiesel fuelled engine. The brake thermal efficiency of the engine decreases with increase in biodiesel percentage in the diesel.

Huseyin Aydin et al. [14] observed the lower brake thermal efficiency of B20 blend compared to conventional diesel fuel. H. An et al. [15] reported that the average brake thermal efficiency value of B100 increases by 5.1% at 100% load, but decreases by 10.7% at 10% load, leaving 50% load as a transition where no increase or decrease in average brake thermal efficiency was observed. That was because at higher load conditions, the fuel injection pressure reaches as high as 1400 bars such that the viscosity effect of B100 was negligible, on the other hand, the fact that B100 contains oxygen results in a more complete combustion, and hence a higher brake thermal efficiency was achieved. Another possibility goes to the fact that the exhaust temperature of B100 was found to be lower compared to diesel which reduces the heat transfer losses, increasing the thermal efficiency. At lower loads, the viscosity effect of biodiesel becomes the dominating factor, resulting in a poor combustion process and reduced BTE. Besides, the release of oxygen atoms from B100 may have leaded to an extra lean combustion process under partial load conditions and reduced the brake thermal efficiency. Fig. 2 represents the brake thermal efficiency of different blends of waste cooking oil at full load condition.

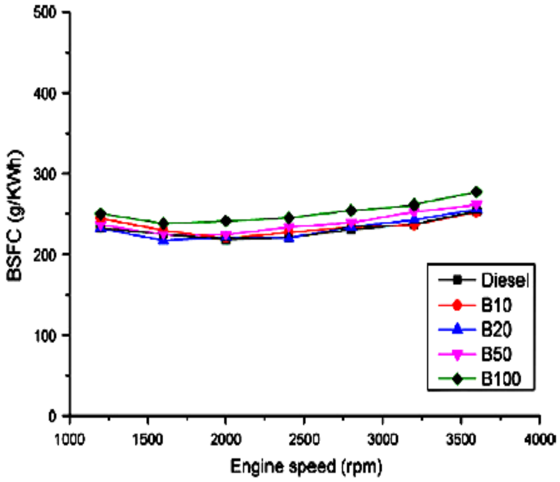

Fig.1. BSFC vs. Speed at full load [15]

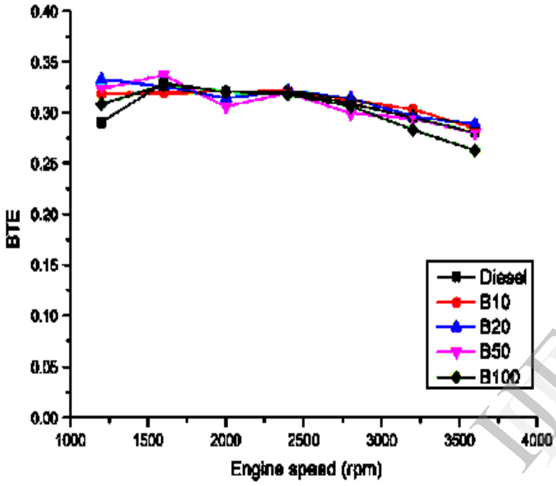

Fig. 2. BTE vs. Speed at full load [15].

5. Engine Exhaust Emissions

5.1 Hydrocarbon (HC) emissions

It is predominant viewpoint that HC emissions reduce when pure biodiesel is fuelled instead of diesel [13, 16, 24, 27]. A.M. Liaquat et al. [13] observed an average reduction in HC compared to DF for JB5, JB10 and J5W5 at 2300 rpm and 100% throttle position, as 8.96%, 11.25% and 12.50%, whereas, at 80% throttle position, HC emission reduction found as 16.28%, 30.23% and 31.98% respectively. Oxygen content of biodiesel found the main reason for more complete combustion and HC emission reduction. Higher cetane number of blends reduces the combustion delay, and such a reduction has also been related to decreases in HC emissions [17-18]. H. An et al. [15] reported that the use of biodiesel improves the combustion process and reduces the HC emissions. The results are shown in fig.3 which represents the variation of HC emissions of diesel, biodiesel and their blend fuels with respect to engine speed at full load conditions.

Jinlin Xue et al. [16] reported an average 45–63% reduction in HC emissions for biodiesel compared with diesel. Some other researchers [19, 21,24] reported the considerably similar decrease. However L.L abecki et al. [17] observed that total hydrocarbon (THC) emissions are higher for 30% RSO blend under the reference engine operating condition when compared to diesel.

Based on the analysis most of researches showed that HC emissions for biodiesel reduce with the increase of biodiesel content. The feedstock of biodiesel and its properties have an effect on HC emissions, especially for the different chain length or saturation level of biodiesels. The advance in injection and combustion of biodiesel favours the lower HC emissions.

5.2. Carbon monoxide (CO) emissions

According to most of literatures it is common trend that CO emissions reduce when diesel is replaced by pure biodiesel. The primary reasons given by the authors include extra oxygen content and higher cetane number of biodiesel which results in complete combustion. A.M. Liaquat et al. [13] reported that as compared to DF, average reduction in CO at 2300 rpm and 100% throttle position was found as; 17.26% for JB5, 25.92% for JB10 and 26.87% for J5W5, whereas, at 80% throttle position, reduction in CO was observed as 20.70% for JB5, 33.24% for JB10 and 35.57% for J5W5 respectively. Extra oxygen content, higher cetane number of biodiesel reduces CO emissions. Jincheng Huang et al. [18] observed the reductions of CO emissions from the blend fuels were from 31.7% (for the blend of Z5E10D85) to 43.9% (for the blend of Z5E30D65). However L.L abecki et al. [17] observed that CO emissions are higher for 30% RSO blend under the reference engine operating condition when compared to diesel. H. An et al. [15] pointed that, with the increase in engine load, the CO emission reduces significantly. Fig. 4 shows the variation of CO emissions with engine speed for diesel, biodiesel and their blend fuels at full load.

It is accepted commonly that CO emissions reduce when using biodiesel due to higher oxygen content and lower carbon to hydrogen ratio in biodiesel compared to diesel. With content of pure biodiesel increasing in blends fuel, CO emissions of blends reduce. CO emissions for biodiesel are affected by its feedstock and other properties of biodiesel such as cetane number and advance in combustion.

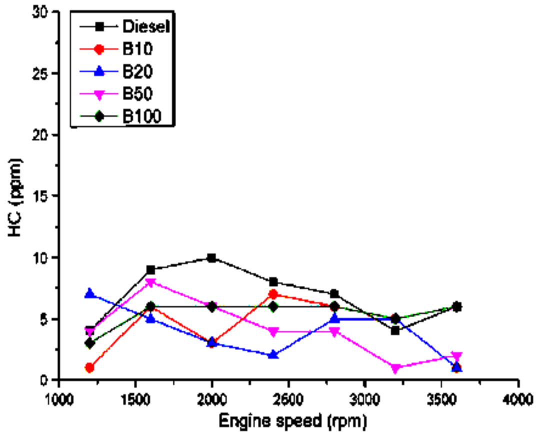

Fig.3. Hydrocarbon emission at full load [15]

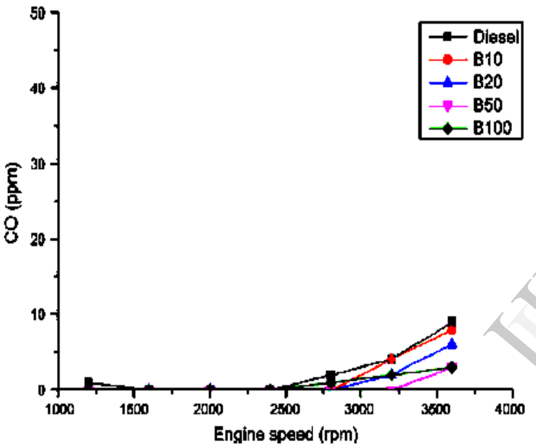

Fig. 4. Carbon monoxide emission at full load [15]

5.3. Carbon dioxide (CO_2) emissions

Because of the contribution rate of traffic on CO_2 emissions is as high as 23% [16, 25], some authors studied CO_2 emissions of biodiesel. In the literatures [19, 23], it was reported that, biodiesel resulted in fewer CO_2 emissions than diesel during complete combustion due to the lower carbon to hydrogen ratio. A.M. Liaquat et al. [13] reported that the reduction in CO_2 compared to DF at 2300 rpm and 100% throttle position was as; 12.10% for JB5, 20.51% for JB10 and 24.91% for J5W5, whereas, at 80% throttle position, reductions was observed as 5.98% for JB5, 10.38% for JB10 and 18.49% for J5W5 respectively. H. An et al. [15] observed the percentage reduction in CO_2 emission increases with the increasing engine load. The average reduction in CO_2 emission for B100 is 4.9%, 7.4%, 10.2%, 10.7% and 16.3% for 10%, 25%, 50%, 75% and 100% loads respectively. The results are shown in fig.5.

It was pointed out in the literatures Daming Huang et al. [1] that, in the case of biodiesel, the higher carbon dioxide emission should cause less concern because of Nature's recovery by raising biodiesel crops. While the literatures [2, 19] evaluated the effect of biodiesel on global greenhouse gas emissions through the life cycle of CO_2 emissions. And they pointed out that; biodiesel will cause 50–80% reduction in CO_2 emissions compared to petroleum diesel.

5.4. Nitrogen oxide (NOx) emissions

Literatures believe that the use of pure biodiesel causes the increase in NO_x emissions [3,19]. For example, a maximum of 15% increase in NOx emissions for B100 was observed at high load condition as the results of 12% oxygen content of the B100 and higher gas temperature in combustion chamber. A.M. Liaquat et al. [13] reported that the increase in NOx compared to DF at 2300 rpm and 100% throttle position was as 4% for JB5, 6.25% for JB10 and 8% for J5W5 whereas, at 80% throttle position, increase was found as 9.5% for JB5, 17.0% for JB10 and 20.0% for J5W5 respectively. It has been reported that formation of NOx emissions are strongly dependent upon the equivalence ratio, oxygen concentration and burned gas temperature.

Many literatures [16, 19, 22, 26] showed that NOx emissions increase with the increase in content of biodiesel. Lei Zhu et al. [19] observed that intake CO_2 concentration and the blended fuels tend to reduce NOx emission. H. An et al. [15] reported that the NOx emission is very sensitive to the engine combustion temperature which increases with the increasing engine speed and load. Fig. 6 compares the variation of NOx emissions with engine speed for diesel, biodiesel and their blend fuels at full load. Ma Zhihao et al. [27] reported that NOx emissions of B10 and B20 is less than that of diesel, and the amount of NOx emissions for B30 is almost the same as for diesel.

On the other hand, L.L abecki et al. [17] investigated Combustion and emission characteristics of rapeseed plant oil (RSO) and its blends with diesel fuel in a multi-cylinder direct injection diesel engine. They reported 22% reduction in NOx emission for 30% blend of RSO under the diesel equivalent soot operating conditions. And they contributed to the high kinematic viscosity, relatively larger droplet diameters and poor evaporation characteristics of RSO.

The majority of literatures reported that NOx emissions will increase when using biodiesel. This increase is mainly due to higher oxygen content for biodiesel. Moreover, cetane number and different injection characteristics also have an impact on NOx emissions for biodiesel. The content of unsaturated compounds in biodiesel could have a greater impact on NOx emissions.

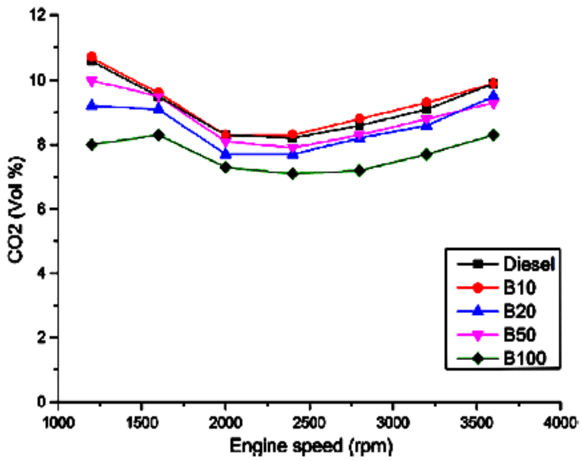

Fig.5. Carbon dioxide emission at full load [15]

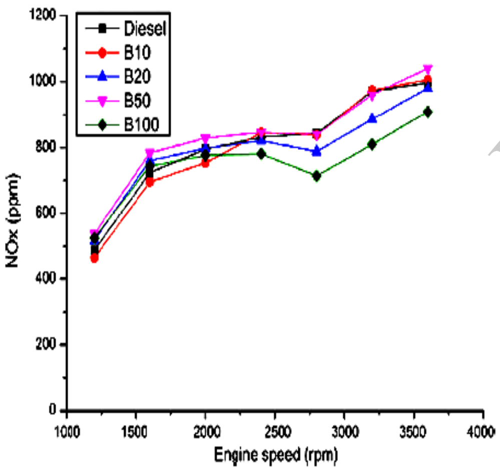

Fig. 6. Nitrogen oxide emission at full load [15]

6. Conclusion

An alternative to conventional fuel, biodiesel, produced from renewable and often domestic sources, emerged as a sustainable source of energy and will therefore play an increasingly significant role in providing the energy requirements for transportation. Therefore, more and more researches are focused on the biodiesel engine performances and its emissions in the past decades. Although there have always been inconsistent trends for biodiesel engine performances and its emissions due to the different tested engines, the different operating conditions or driving cycles, the different used biodiesel or reference diesel, the different measurement techniques or instruments etc. The following general conclusions could be drawn according to analysis and summary of the massive related literatures in this work:

1. The majority of studies have shown that CO emissions reduce when using biodiesel due to the higher oxygen content and the lower carbon to hydrogen ratio in biodiesel compared to diesel.
2. There exist the inconsistent conclusions, some researches indicated that the CO_2 emission reduces for biodiesel as a result of the low carbon to hydrocarbons ratio, and some researchers showed that the CO_2 emission increases or keeps similar because of more effective combustion. But in any event, the CO_2 emission of biodiesel reduces greatly from the view of the life cycle circulation of CO_2.
3. It is predominant viewpoint that HC emissions reduce when biodiesel is fuelled instead of diesel. This reduction is mainly contributed to the higher oxygen content of biodiesel, but the advance in injection and combustion of biodiesel also favour the lower THC emissions.
4. The use of biodiesel will lead to loss in engine brake power mainly due to the reduction in heating value of biodiesel compared to diesel, but there exists brake power recovery for biodiesel engine as the result of an increase in biodiesel fuel consumption.
5. The majority of literatures agree that NOx emissions will increase when using biodiesel. This increase is mainly due to higher oxygen content for biodiesel. Moreover, the cetane number and different injection characteristics also have an impact on NOx emissions for biodiesel.
6. An increase in biodiesel fuel consumption, due to low heating value and high density and viscosity of biodiesel, has been found, but this trend will be weakened as the proportion of biodiesel reduces in the blend.

Overall, biodiesel, especially for the blends with a small portion of biodiesel, is technically feasible as an alternative fuel in CI engines with no or minor modifications to engine. For environmental and economic reasons, their popularity may soon grow.

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