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EFFECT OF BIODIESEL BLENDED FUEL ON THE PERFORMANCE AND EMISSION CHARACTERISTICS OF DIESEL ENGINES – A REVIEW

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The internal combustion engine plays a vital role in transportation, industry, and shipping. However, diesel as one of the main fuels for internal combustion engines, caused many environmental and human health problems. In order to solve the problems, more researchers have been committed to the research of alternative fuels. Biodiesel is a renewable, sustainable alternative fuel, and its characteristics are similar to traditional diesel. It can be mixed with pure diesel. It has been found that a mix with pure diesel in a certain ratio can effectively reduce the negative effects caused by its characteristics, improve the combustion performance, and reduce the NOx and PM emissions. This article mainly reviews the effects of the mixture of biodiesel and diesel on engine combustion characteristics and exhaust emissions, including three parts: part (1) summarizes and analyzes the biodiesel's production and characteristics, part (2) analyzes the engine's performance under different working conditions, and part (3) studies and analyzes the exhaust emission under different working conditions.

Keywords: biodiesel, Diesel engine, fuel properties, engine performance, exhaust emission.

1. Introduction

According to the statistics of the transportation sector, the average fuel consumption of diesel oil increases at the rate of *1.1*% every year, resulting in the rapid reduction of existing crude oil fuel. With the development of society and the enhancement of environmental protection awareness, people have higher and higher requirements for fuel, so to find an alternative fuel is an important goal. Biodiesel is one of the alternative fuels with wide application prospects, it is non-toxic, biodegradable, and can be extracted from renewable plants or animal fats, food waste, and non-edible plants. Biodiesel can be used for replacing some diesel in the engine to reduce diesel consumption, reduce the generation of exhaust emission and protect the environment. Biodiesel has similar characteristics to traditional diesel, and can be used directly in existing engines without any modifications. When low concentration of biodiesel was used in the engine, it was found that the emissions of HC, CO, and smoke were lower than diesel, and the engine characteristics were better [1]. Due to the high viscosity and low cetane number of biodiesel, when the high concentration of biodiesel is used, increased ignition delay and reduced ignition temperature, and high viscosity may cause blockage of fuel injection nozzle, incomplete combustion in cylinder, and increase exhaust emission [1, 2]. Therefore, when a low concentration of biodiesel is used, it can improve the engine performance and reduce the exhaust emissions [3]. Therefore, a through review of biodiesel-diesel blends performance is made here to analyze the effect of biodiesel on engine performance and exhaust emissions. The structure of the text is as follows: the first part mainly summarizes and analyzes the production and characteristics of various biodiesel blends; the second part analyzes the performance of the engine under different working conditions; the third part studies and analyzes the exhaust emission under different working conditions.

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2. Production and characterization of biodiesel

2.1 Production of biodiesel

Although biodiesel and diesel have similar characteristics, the production of biodiesel requires high costs and specialized technologies, therefore, the production of biodiesel is one of the important problems that need to be solved urgently. For the production of biodiesel, researchers have developed many production technologies to extract biodiesel from various animal and vegetable fats and waste oils. Among these methods for biodiesel production, transesterification is considered to be a good method because of its high yield, low cost and short reaction time. In the transesterification reaction, esters and glycerol are formed by the reaction of oil and alcohol. Generally, transesterification is affected by reaction time, temperature, moisture, and other factors, the additives can be added during the reaction to speed it up.

M.A. Asokan *et al.* [3] purchased safflower oil as raw material, mixed it with methanol, added KOH, and sulphuric acid as catalyst and produced biodiesel by transesterification. After the reactants were placed for some time, the upper layer was biodiesel, and the productivity of biodiesel obtained by this method was as high as 90%. Ravishankar Sathyamurty *et al.* [4] processed corn seeds by Soxhlet extraction to produced biodiesel, which was mainly produced by transesterification. NaOH and methanol needed to be added as catalysts to remove water and methanol by vacuum distillation to produce biofuels. Madhurjya Saikia *et al.* [1] added a homogeneous catalyst into pomelo seed oil and separated it by a specific gravity separation method to prepare biodiesel. M.A. Asokan *et al.* [2] added methanol and KOH as catalysts to produce flaxseed oil biodiesel by transesterification. Waste cooking oil mainly came from hotels and restaurants, and water was removed by heating, and NaOH additives were added to produce biodiesel through transesterification reaction [5].

2.2 Characteristics of diesel and biodiesel

In general, biodiesel has similar physical and chemical properties to traditional diesel, but different biodiesels have different properties. Table 1 shows some common biodiesel characteristics.

Compared with diesel, the calorific value of biodiesel is lower than that of diesel, therefore, under the same working conditions, more biodiesel needs to be consumed to make the engine reach the same power [6]. Biodiesel has a higher flash point than diesel, and can be safely transported and stored, therefore, in terms of safety, biodiesel has a greater advantage than diesel. Biodiesel contains oxygen, which helps to supplement the oxygen element in the combustion process, promote combustion, and reduce the reduction of HC, CO and PM.

Compared with diesel, biodiesel has higher viscosity and higher density; high viscosity will block the nozzle during injection, will cause slow combustion and exhaust emission due to incomplete mix of air and fuel during combustion in the cylinder [4]. Biodiesel contains high cetane number, which is close to that of diesel, therefore, the ignition time is close to that of diesel, which results in good ignition performance, shorter ignition delay, increased combustion cycle and more uniform combustion [6].

Table 1. Properties of biodiesel and diesel [1-6, 9, 11, 12, 14, 17, 20, 21].

Properties / Biodiesel	Kinematic Viscosity (mm^2/s)	Cetane Number	Calorific Value (MJ/l)	Cloud Point (^oC)	Fire Point (^oC)	Flash Point (^oC)	Density (kg/l)	Pour point (^oC)
Diesel	*2.75*	*53*	*43.8*	*-5*	*70*	*62*	*0.83*	*3*
Safflower oil biodiesel	*8.21*	*51*	/	*-2*	*168*	*156*	*0.895*	/
Corn oil methyl ester biodiesel	*6.38*	/	*36.598*	/	*149*	*139*	*0.91*	/

Cont. Table 1. Properties of biodiesel and diesel [1-6, 9, 11, 12, 14, 17, 20, 21].

Pomelo oil Biodiesel	4.92	47.9	27.1	-4	200	151	0.88	-15
Flaxseed oil biodiesel	4.92	51	40.12	/	183	172	0.872	/
Waste cooking oil biodiesel	3.5	52	39.4	/	/	130	0.875	/
Fish oil biodiesel	4.91	59	39.51	9	168	156	0.877	5
Papaya biodiesel	5.01	/	38.97	/	158	147	0.895	/
Watermelon seed oil biodiesel	5.65	/	39.55	/	163	152	0.89	/
Mahua oil-based biodiesel	6.6	/	/	/	125	105	0.895	-12
Salvinia molesta oil biodiesel	5.013	/	36.935	2	199	194	0.87	-5
Sunflower and soybean oil mixture biodiesel	4.7	62	37.5	7	167	160	/	-9
Beef tallow biodiesel	5.85	56	38.35	/	/	/	0.873	/
Milk scum biodiesel	4.2	/	39.785	15	/	157	0.879	9
Gossypium arboreum biodiesel	4.32	/	41.25	/	/	/	0.875	/

3. Combustion characteristics of diesel engine

3.1. In-cylinder pressure

In a diesel engine, cylinder pressure is the decisive factor of engine performance and combustion characteristics. The addition of biodiesel may reduce the cylinder pressure, which may be due to the short combustion time and incomplete combustion, because of the high viscosity and low cetane number of biodiesel. Upendra Rajak *et al.* [8] studied the influence of microalgae biodiesel-diesel mixed fuel combustion process on cylinder pressure. From the results shown in Fig.1, it is found that diesel has the highest cylinder pressure compared with biodiesel-diesel mixed fuel; microalgae biodiesel had low calorific value, high viscosity and density, made large fuel droplets, made air and fuel mixture incomplete, inhibited combustion, resulting in low cylinder pressure. Medhat Elkelawy *et al.* [9] studied sunflower biodiesel-soy biodiesel-diesel blends, and found that the high calorific value and spontaneous combustion characteristics of diesel, as well as the higher cetane number and oxygen content of biodiesel produce high cylinder pressure during combustion.

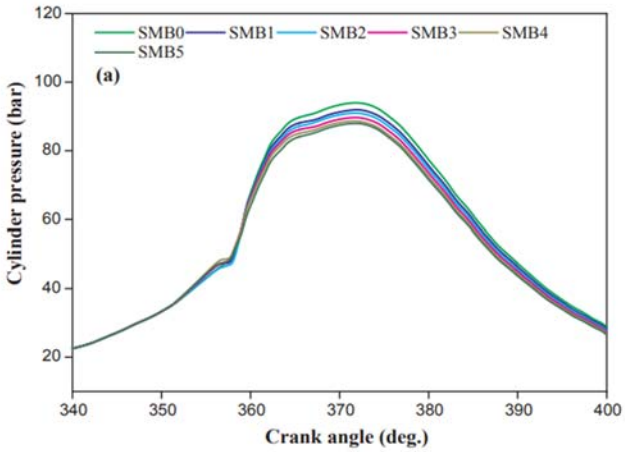

Fig.1. Variation of In-cylinder pressure at different blends [8].

Figure 2 shows the cylinder pressures under different engine loads [10]. It is found from the figure that the cylinder pressure generated was higher, mainly because the diesel has a higher cetane number and lower viscosity, which promoted combustion completely and increased the cylinder pressure. Under high loads, the temperature increased with the increased pressure, and the evaporation rate also increased, which resulted in better combustion, and increased cylinder pressure [11].

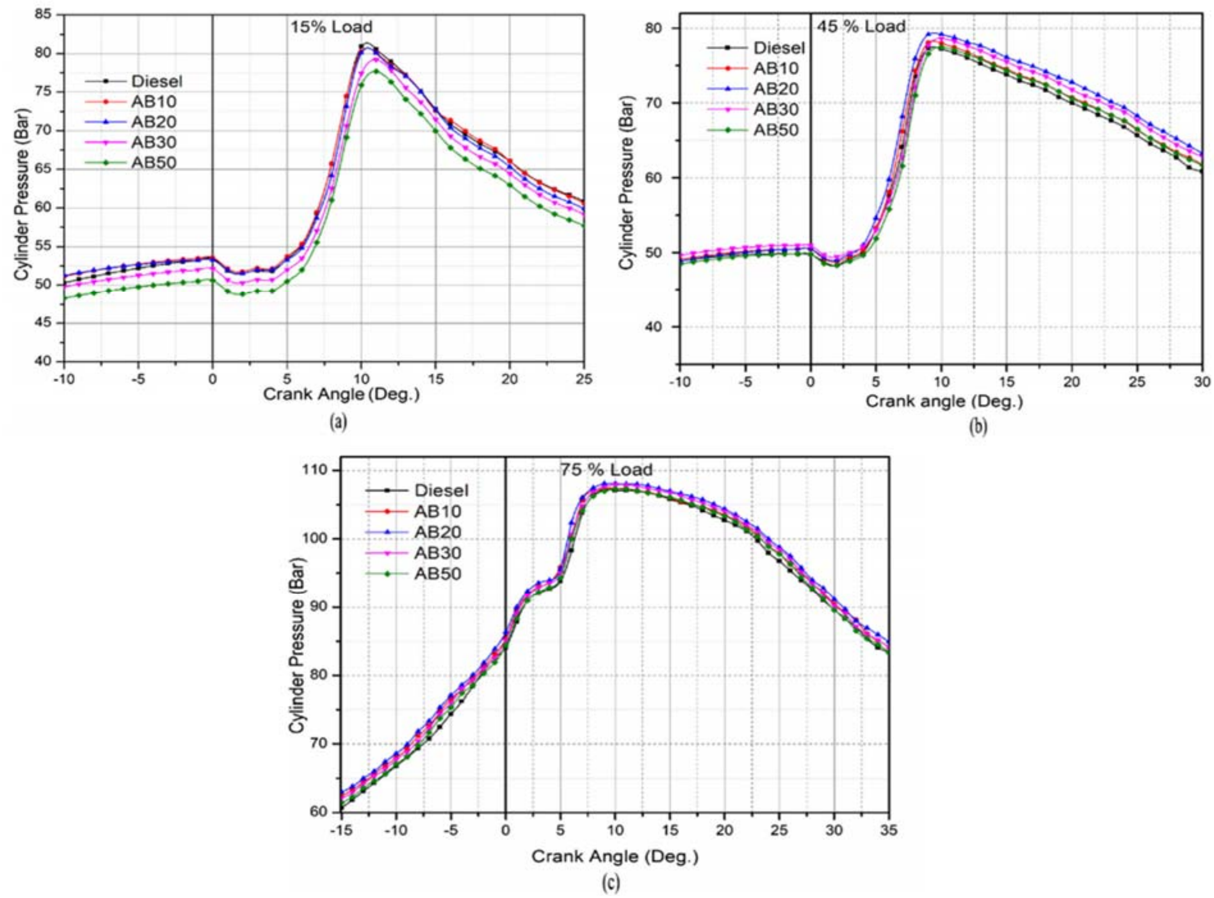

Fig.2. Variation of in-cylinder pressure at different engine loads [10].

3.2. Brake specific fuel consumption

The brake specific fuel consumption（BSFC）is affected by factors such as the calorific value, density, viscosity, etc.. S. K. Nayak *et al.* [12] studied the effect of fish oil biodiesel-waste cooking oil biodiesel-diesel mixed fuel on the BSFC. It is found in Fig.3 that compared with biodiesel, diesel has the lowest BSFC, because the calorific value of biodiesel is lower than diesel. When using biodiesel, more fuel must be consumed under the same engine working conditions to obtain the same power as diesel,. M. A. Asokan *et al.* [11] studied the impact of biodiesel mixing on engine performance and emission after papaya oil biodiesel and watermelon seed oil biodiesel were mixed with diesel. It was found (Fig.4) that the low calorific value of biodiesel resulted in the increase of mixed fuel consumption.

The BSFC of biodiesel-diesel mixed fuel decreases with the increase of load. At low load, due to low engine cylinder temperature and poor atomization, less fuel was burned in the pre-mixing stage and more fuel was burned in the mixing control stage; at medium and high loads, higher temperature and better atomization in the cylinder could minimize the negative effects of biodiesel, cause complete combustion, and reduce the BSFC.

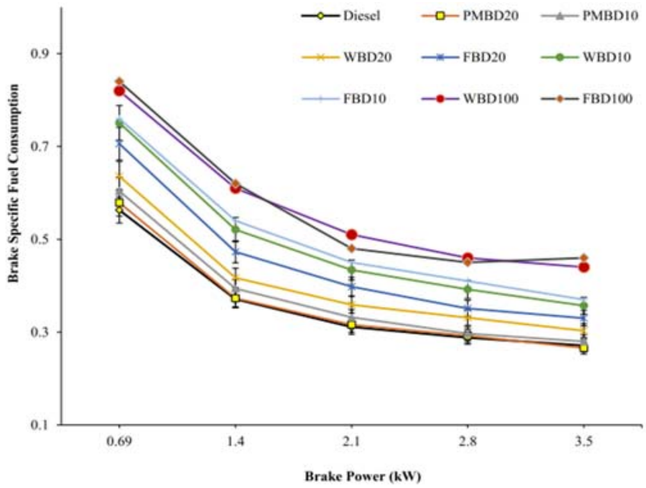

Fig.3. Variation of BSFC at different blends [12].

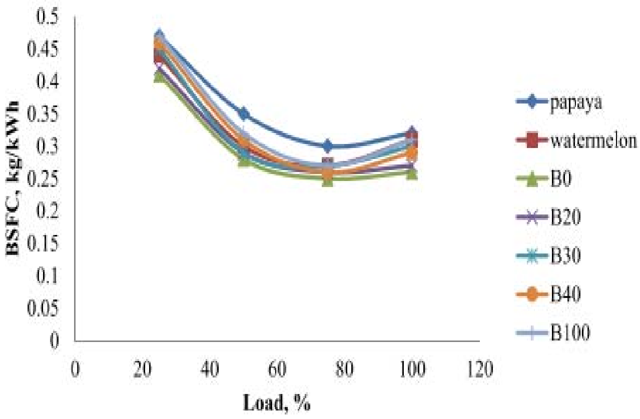

Fig.4. Variation of BSFC at different blends [11].

Figure 5 shows the effect of safflower oil biodiesel/diesel blends on the engine [13]. It is found that as the engine speed increased, the BSFC has a tendency to first decrease and then increase, because of poor fuel atomization and poor fuel-air mixing. It resulted in an increase in the BSFC under lower engine speeds. With the increase of engine speed, it may increase the atomization effect of fuel, increase the mixing speed of fuel and reduce the BSFC value. However, with a further increase of engine speed, the frequency of fresh air entering the cylinder increased, which resulted in lower temperature in the cylinder, inhibited combustion and increased BSFC.

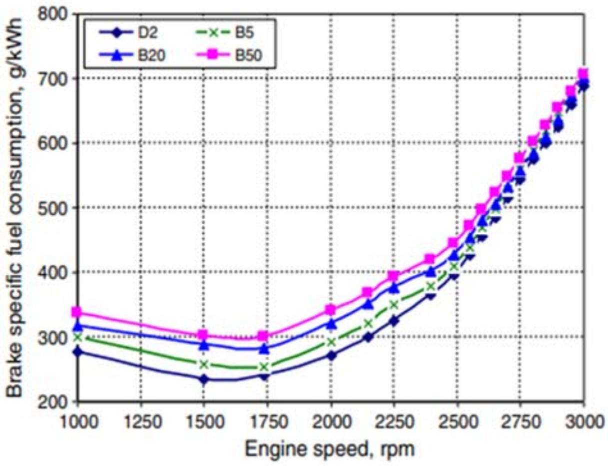

Fig.5. Variation of BSFC at different engine speeds [13].

3.3. Brake thermal efficiency

The braking thermal efficiency（BTE）is the value obtained by dividing the braking output by the heat energy supplied by the fuel. It is an important index to determine the engine performance. M. Kannan *et al.* [14] studied the effect of Mahua oil-based biodiesel-diesel mixed fuel on the BTE. In Fig.6, it can be found that the BTE of biodiesel-diesel mixed fuel was lower than that of diesel, and that the BTE decreased with an increase of biodiesel proportion, because biodiesel has higher kinematic viscosity and lower calorific value, which will lead to poor atomization and more fuel consumption. Suleyman Simsek *et al.* [7] studied the effect of biodiesel-diesel mixed fuel on the BTE, and found the opposite results (Fig.7). It was considered that biodiesel contains inherent oxygen, which increases combustion in the cylinder, promotes combustion, higher combustion temperature and increases the BTE.

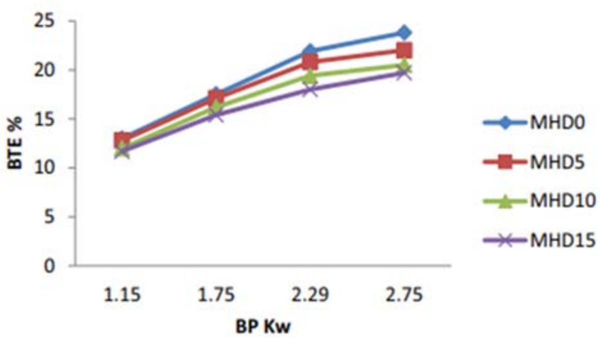

Fig.6. Variation of BTE at different blends [14].

Figure 8 shows that the BTE of biodiesel-diesel mixed fuel increased with an increase of load [15]. At low load, the combustion temperature was low and the fuel/air mixing was incomplete, which resulted in incomplete combustion, and low BTE [4]. With the increase of load, the combustion temperature increased and resulted in complete combustion and increased BTE.

For biodiesel-diesel mixed fuel, the BTE is related to the oxygen content, density, kinematic viscosity, calorific value and specific fuel consumption of biodiesel fuel. The oxygen content of biodiesel is higher than that of diesel, and oxygen is released during combustion, resulting in complete combustion in the cylinder, and increases BTE. Conversely, biodiesel has higher viscosity and density, causes poor atomization, increases the BSFC, affects combustion of blends, reduces combustion efficiency.

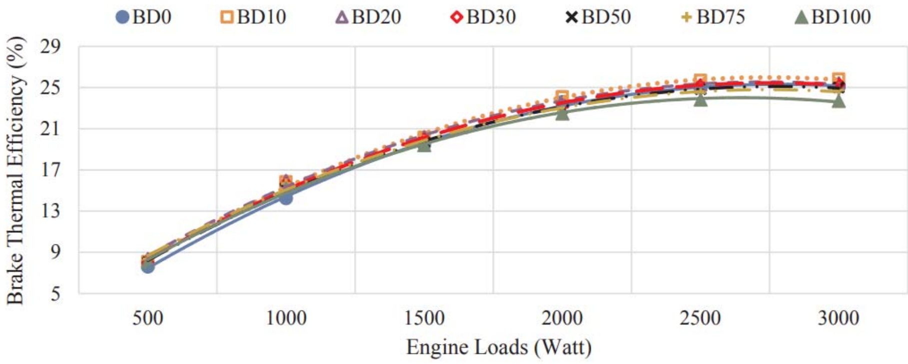

Fig.7. Variation of BTE at different blends [7].

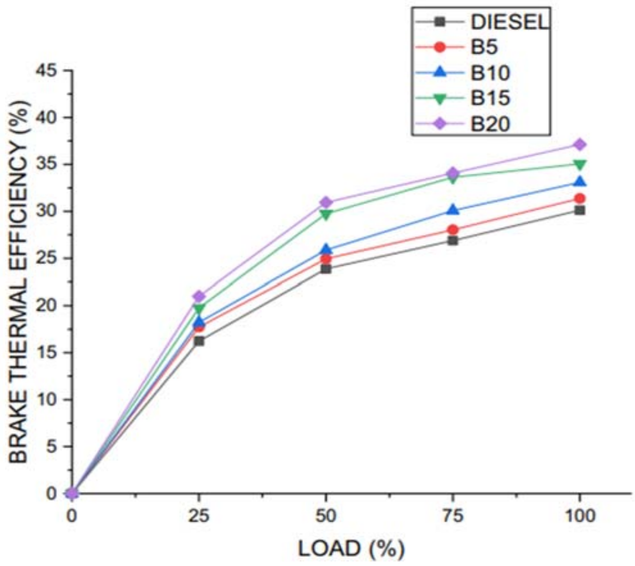

Fig.8. Variation of BTE at different engine loads [15].

3.4. Exhaust gas temperature

It can be found in Fig.9 that compared with diesel, the biodiesel-diesel mixed fuel has a higher EGT, because biodiesel is an oxygen-containing fuel. It can provide a large amount of oxygen, increase the combustion temperature, and cause a higher exhaust gas temperature. The high viscosity of biodiesel caused poor atomization and evaporation, which led to prolonged combustion time, and caused higher EGT [11]. S.

K. Nayak *et al.* [12] studied the effects of fish oil biodiesel, waste cooking oil biodiesel, and biodiesel-diesel mixed fuel on the EGT, and obtained similar results.

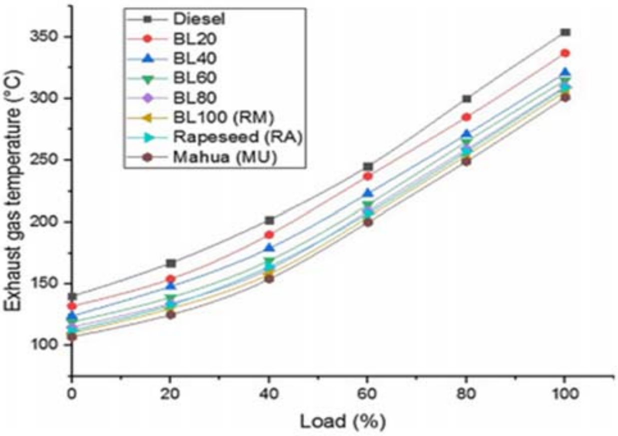

Fig.9. Variation of EGT at different blends [16].

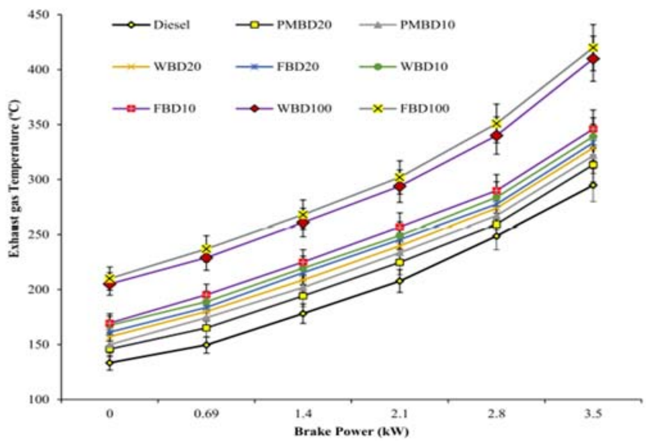

Fig.10. Variation of EGT at different blends [12].

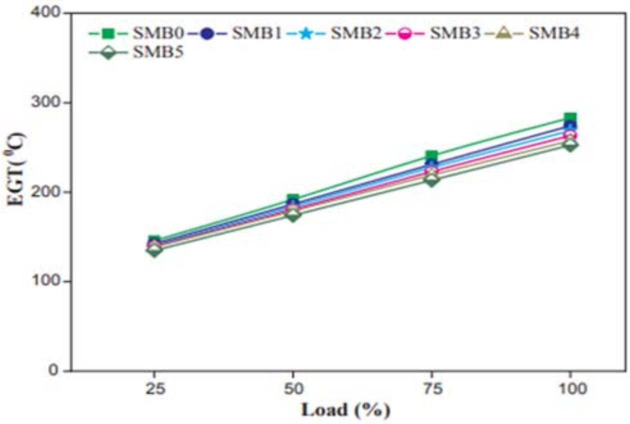

Fig.11. Variation of EGT at different engine loads [8].

It is found in Fig.10 that the reasons why biodiesel-diesel mixed fuel had high EGT was that biodiesel-diesel mixed fuel shortened the premixed combustion period, prolonged the combustion duration, speeded up the combustion stage of compression stroke, shortened the heat transfer time and increased the exhaust emission temperature.

Figure 11 shows the effect of load on the EGT. The EGT increased as the load increased [8]. Because the calorific value of biodiesel is lower than that of diesel, more fuel is injected into the cylinder and more heat is released during combustion. D. John Panner Selvam *et al.* [6] found that the EGT of biodiesel was higher than that of diesel at low engine speeds, and the opposite was found at high engine speeds.

4. Exhaust gas emissions

The emissions of diesel engine include CO, CO_2, HC, NO_x and smoke, and the emissions mainly depend on factors such as fuel type and mixing ratio. In general, compared with diesel, when biodiesel-diesel fuel is used, it promotes combustion during the combustion processes, reduces CO, HC, CO_2 and smoke emissions because biodiesel contains a large amount of oxygen. Under different operating conditions and control measure conditions, production of exhaust emissions will be different. The emissions are described in detail below:

4.1. CO emission

Carbon monoxide (CO) in exhaust emission is the result of incomplete combustion of fuel. In other words, the more incomplete the combustion, the more CO emissions will be produced.

Figure 12 shows the effect of biodiesel ratio on CO emissions [15]. As the proportion of biodiesel in biodiesel/diesel blends increased, CO emission decreased. First, biodiesel is an oxygenated fuel, which can release more oxygen when the engine burns, promote combustion and reduce CO emissions; Second, biodiesel has a high cetane number, which can shorten ignition delay, increase cylinder temperature, more fuel is fully burned, and it reduces CO emissions [13]. M. Mubarak *et al.* [17] studied the impact of salvinia molesta oil biodiesel-diesel mixed fuel on CO emission. In Fig.13 we can see that the emission of carbon monoxide of the mixed fuel is reduced, because biodiesel containes a large amount of oxygen and promotes fuel combustion. Medhat Elkelawy *et al.* [9] studied the variation of sunflower biodiesel, soybean oil biodiesel, and biodiesel-diesel mixed fuel with different loads. Figure 14 shows that all fuels increase emission of CO as the load increased. As the loads increase, the fuel-rich zone is produced, causes localized deficiency of oxygen, incomplete combustion, and increased CO emissions [17].

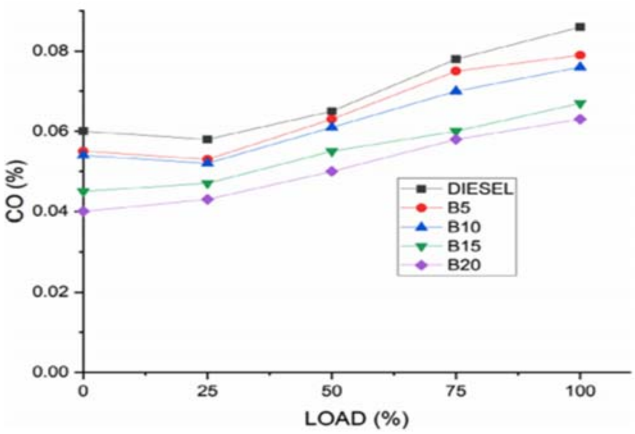

Fig.12. CO emission with different blends [15].

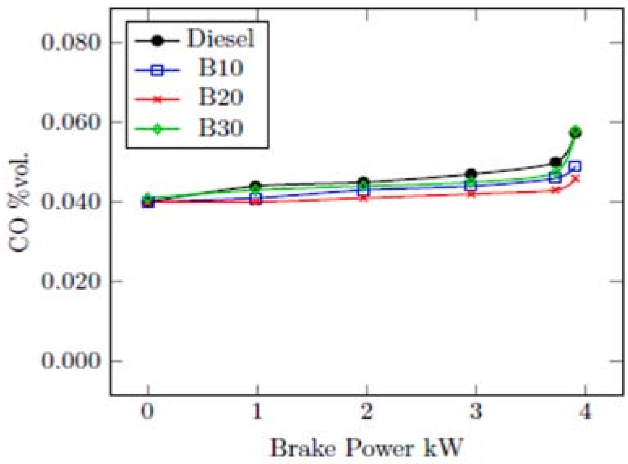

Fig.13. CO emission with different blends [17].

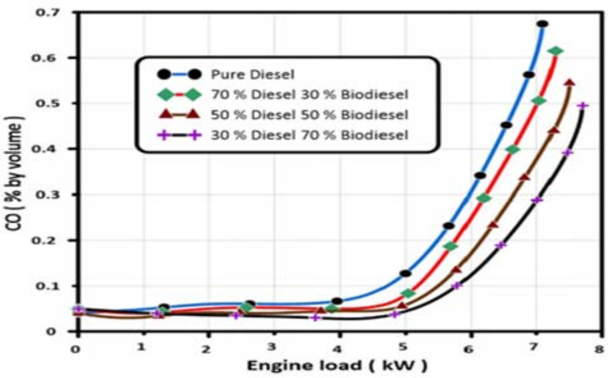

Fig.14. CO emission with different engine loads [9].

4.2. HC emission

HC emissions are mainly caused by oxygen deficit and poor fuel ratio. Due to oxygen deficit, the fuel combustion is incomplete, and a large amount of carbon react with hydrogen to produce HC. D. John Panner Selvam *et al.* [6] studied the effect of the mixing ratio of beef tallow biodiesel-diesel mixed fuel on HC emissions. From the results in Fig.15, it is found that the HC emissions of biodiesel-diesel mixed fuels were lower than that of diesel, and as the proportion of biodiesel increased, HC emissions decreased. Cumali Ilkılıç *et al.* [13] found that the high cetane number in biodiesel has a positive effect on reduction of HC emissions, because biodiesel with high cetane number shortened ignition delay and increased combustion duration, which resulted in complete combustion and low HC emissions. M.A. Asokan *et al.* [2] also found that biodiesel with a high cetane number had a positive effect on reducing HC emissions in the study of linseed oil biodiesel-diesel mixed fuel, as shown in Fig.16. Figure 17 shows that biodiesel/diesel blends increased as the load increased [18]. Because fuel rich zone would be generated at high load, resulted in incomplete combustion, and increased HC emissions [17].

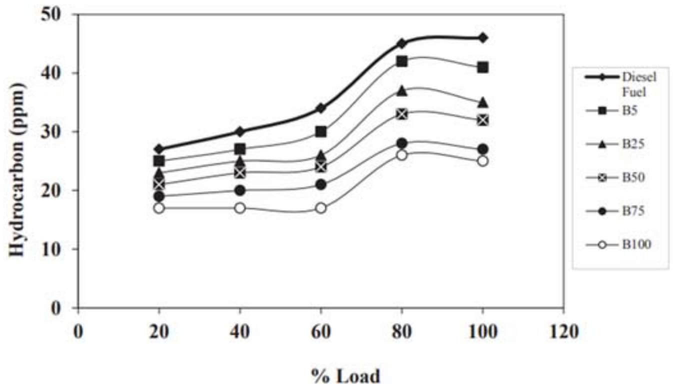

Fig.15. HC emission with different blends [6].

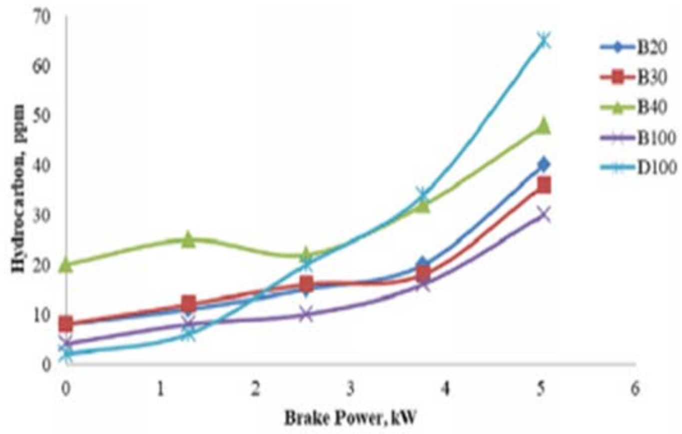

Fig.16. HC emission with different blends [2].

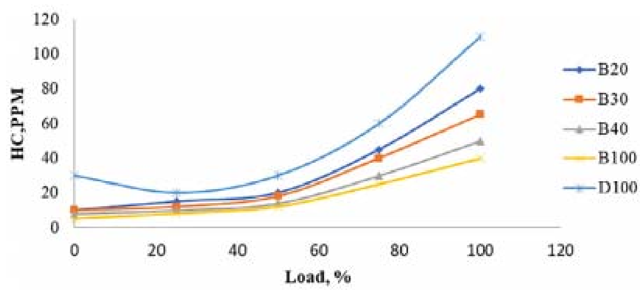

Fig.17. HC emission with different engine loads [18].

4.3. NO_x emission

NO_x emissions are related to oxygen content and combustion temperature. Excess oxygen reacts with nitrogen to produce NO_x [19]. Figure 18 shows the effect of biodiesel-diesel mixed fuel on NO_x emissions [7]. Veerbhadrappa Telgane *et al.* [20] studied milk scum biodiesel emissions and found that NO_x emissions were closely related to the oxygen content in the combustion process and the temperature in the cylinder, as shown in Fig.19. The low heat transfer and oxygen-rich biodiesel promoted the cylinder combustion, increased the exhaust gas temperature, and caused a large amount of NO_x generation. M. Mubarak *et al.* [17] found that NO_x

emission increased with the increased of load. It can be seen in Fig.20. that as the load increased, the fuel consumption, the exhaust gas temperature, and cylinder pressure increased.

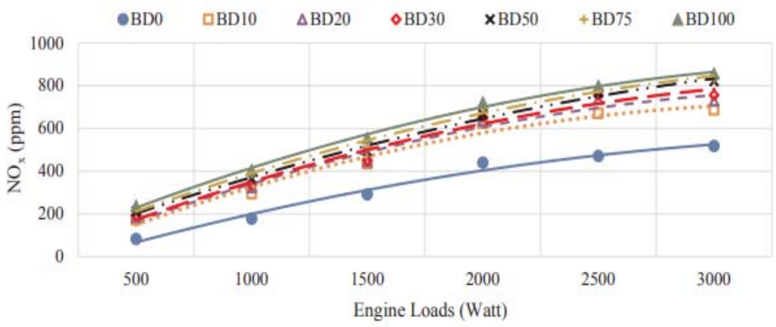

Fig.18. NO_x emission with different blends [7].

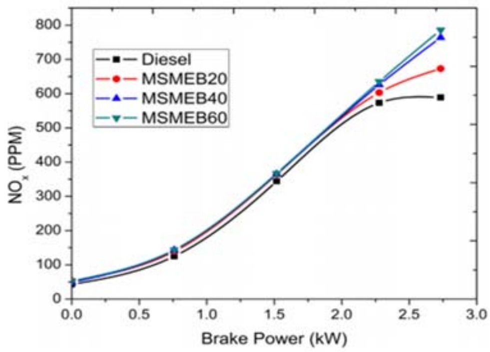

Fig.19. NO_x emission with different blends [20].

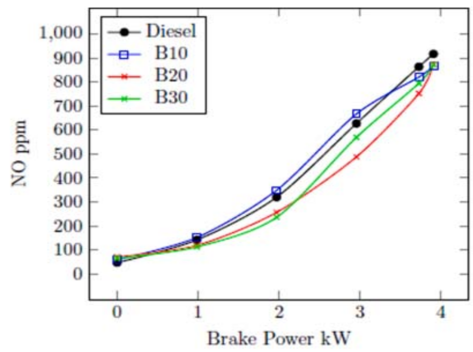

Fig.20. NO_x emission at different engine loads [17].

4.4. CO_2 emission

CO_2 emissions are the product of complete combustion in the engine cylinder [4]. Figure 21 showed the effect of the salvinia molesta oil biodiesel-diesel mixed fuel on CO_2 emissions [17]. The oxygen in the salvinia molesta oil biodiesel-diesel mixed fuel leads to complete combustion and there are more CO_2 emissions. Figure 21 shows that B20 has the highest CO_2 emission, because B20 contains a large amount of oxygen. It promotes combustion and increased CO_2 emission during combustion. The amount of B30 injected into the cylinder was greater than B20 because of its high viscosity. As a result of poor fuel atomization and mixing CO_2 emissions were smaller as compared to B20. Veerbhadrappa Telgane *et al.* [20] and S. Ganesan *et al.* [21] studied the effects of milk scum biodiesel and gossypium arboreum biodiesel on CO_2 emissions, and reached the same result shown in Figs 22 and 23, respectively.

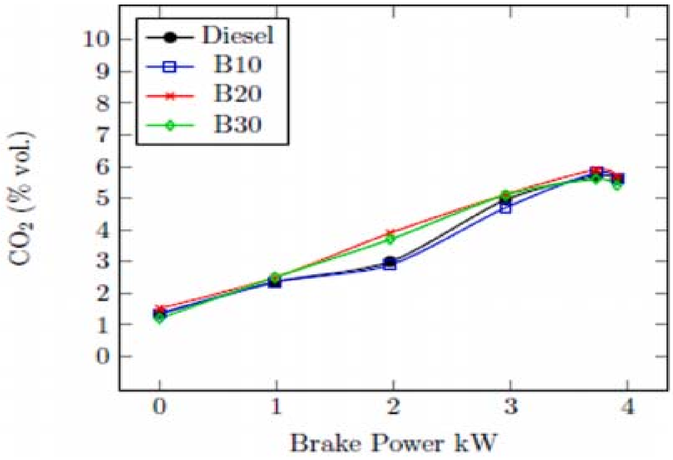

Fig.21. CO_2 emission with different blends [17].

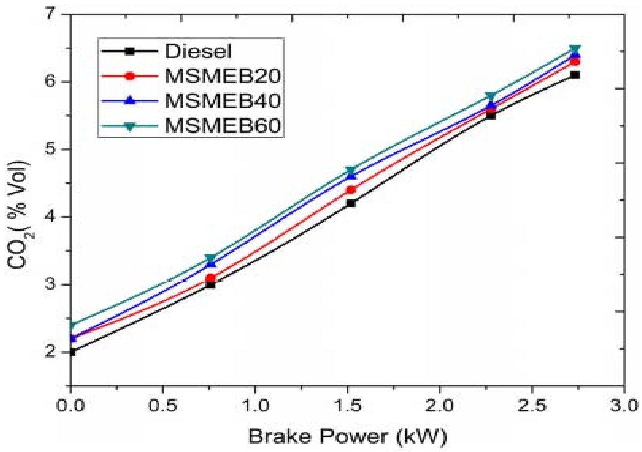

Fig.22. CO_2 emission with different blends [20].

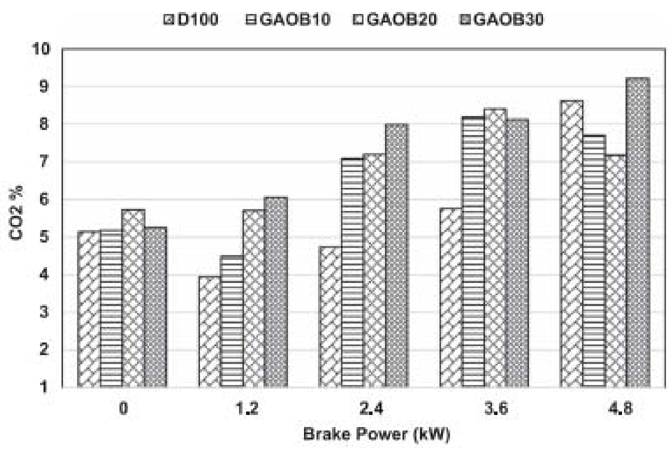

Fig.23. CO_2 emission with different blends [21].

4.5. Smoke emission

Smoke is a substance produced when the fuel is not completely burned in the cylinder, under the condition of insufficient oxygen, the C element accumulated in the cylinder cannot be fully oxidized, and a large amount of smoke will be generated, which is then discharged through the exhaust gas [11]. SK Nayak *et al.* [12] studied the effects of the fish oil biodiesel, waste cooking oil biodiesel, and biodiesel-diesel mixed fuel on smoke emissions. Figure 24 shows that the biodiesel contained more oxygen elements. The oxygen atoms can fully oxidize C atoms and convert to CO, and thus improve the diffusion and combustion of smoke [9]. The high cetane number of the biodiesel can shorten the ignition delay, increase the combustion duration, and gives the fuel enough time to burn completely. For the above reasons, smoke emission could be reduced when biodiesel-diesel mixed fuels are used. M.A.A. Sokan *et al.* [11] studied the effects of the papaya biodiesel and watermelon seed oil biodiesel-diesel mixed fuels on smoke emissions, and reached similar conclusions shown in Fig.25. Medhat Elkelawy *et al.* [9] studied the effect of load on smoke and concluded that an increase of load leads to an increase of smoke. It can be found in Fig.26 that the main reason was that the biodiesel has a high kinematic viscosity and poor atomization during injection, as the load increased, the amount of fuel injected in the cylinder also increased, and it resulted in incomplete combustion and increased smoke production.

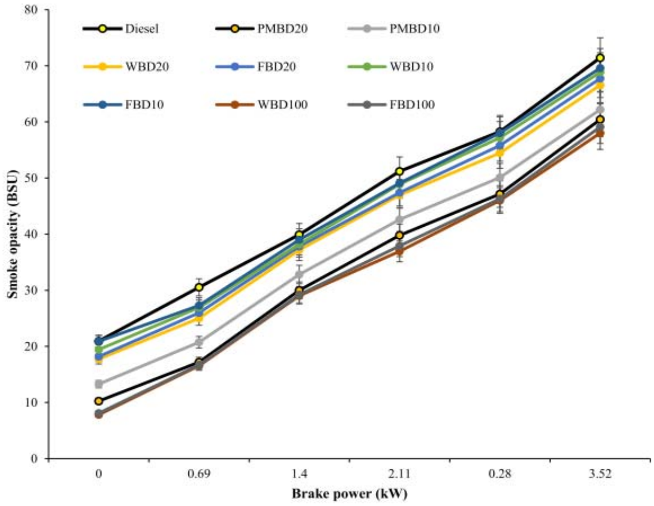

Fig.24. Smoke emission with different blends [12].

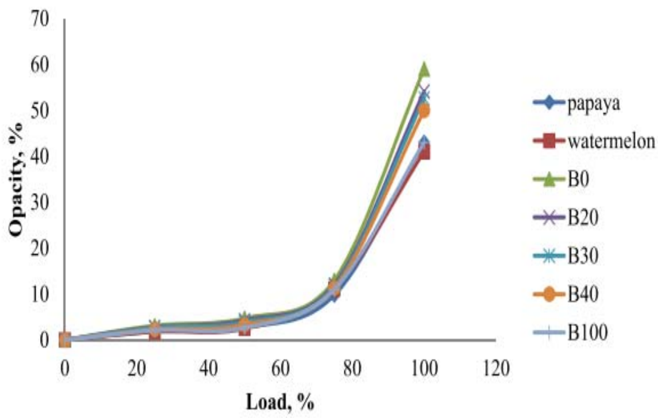

Fig.25. Smoke emission with different blends [11].

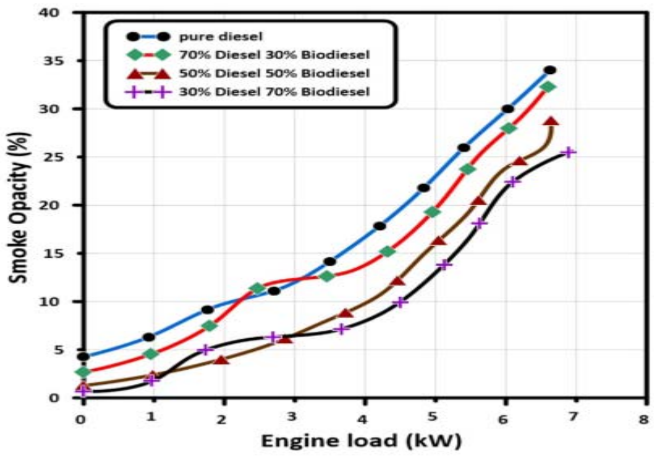

Fig.26. Smoke emission at different engine loads [9].

5. Conclusions

The use of biodiesel can reduce the demand for crude oil materials, effectively reduce its consumption. The use of biodiesel can reduce emissions and reduce environmental damage.

1. Biodiesel can be used in existing engines without any modifications, reduce the cost of engine modification. In diesel engines, biodiesel-diesel mixed fuel can improve engine performance and significantly reduce emissions.
2. Transesterification is the most commonly used method to produce biodiesel. In the transesterification reaction, esters and glycerol are formed by the reaction of oil and alcohol, moreover, the density and concentration of biodiesel can be reduced by transesterification.
3. Compared with diesel, biodiesel has a lower calorific value and higher flash point, density, viscosity and cetane number. It has similar characteristics to traditional diesel. The use of biodiesel/diesel blends can increase cylinder pressure and EGT. The high viscosity of biodiesel will increase the BSFC, cause a long reaction cycle and reduce the BTE. However, when the mixing ratio of biodiesel and diesel is low, biodiesel contains a large number of oxygen atoms, so it can promote combustion. Moreover, the emissions of CO, HC and smoke are reduced, and the emissions of NOx and CO2 are increased.
4. As the engine load increases, the braking thermal efficiency, exhaust gas temperature and all exhaust emissions grow.

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Nomenclature

NaOH – sodium hydroxide

KOH – potassium hydroxide

BSFC – brake specific fuel consumption

BTE – braking thermal efficiency

EGT – exhaust gas temperature

CO – carbon monoxide

HC – hydrocarbon

NO_x – nitrogen oxide

CO_2 – carbon dioxide

C atoms – carbon atoms

C element – carbon element

mm^2/s – millimeter squared per second

MJ / kg – mega joules per kilogram

^oC – Celsius grade

kg / l – kilogram per liter

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