AMERICAN Journal of Engineering, Mechanics and Architecture
Volume 02, Issue 6, 2024 ISSN (E): 2993-2637

Diesel Engine Combustion and Emission Characteristics of Polyoxymethylene Dimethyl Ether Blended with Biodiesel

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Abstract: The use of biodiesel as an alternative fuel for diesel engines shows great potential. Polyoxymethylene dimethyl ether, also known as PODE, is frequently utilised as a fuel additive due to its high cetane number, low viscosity, and high oxygen concentration. During the course of this research, PODE is combined with biodiesel as a significant fuel component in order to enhance the low-temperature flow properties and viscosity of biodiesel. The objective of this study is to achieve superior engine emission characteristics and efficiency in comparison to the baseline operation that was carried out using neat diesel. Diesel (D100), biodiesel (B100), and biodiesel/PODE blend fuel (B85P15) will be used in the trials, and they will be carried out in a direct injection diesel engine while the engine is working under varying loads. The data on combustion, the amount of fuel consumed, and the emissions of gas are measured. The B85P15 model delivers the lowest soot emission, which is less than 0.01 grammes per kilowatt-hour, as well as the maximum combustion efficiency and the highest indicated thermal efficiency.

Keywords: Biodiesel, Polyoxymethylene dimethyl ether (PODE), Diesel, Cetane number.

Introduction

As a substitute feedstock for biodiesel synthesis, some researchers have begun working on using inexpensive food oils. Seeds from microalgae, castor, and jatropha are among the most promising and dependable non-edible oil feedstock sources due to their high seed oil concentration [9-13]. We may use the same infrastructure and equipment to store and transport biodiesel as you would for regular petroleum diesel, and it can be used in nearly any standard internal combustion diesel engine without any modifications. One of the biggest issues the transportation sector is encountering is the high idle conditions that result from engines operating at low loads and rated speeds. Because of this, the engine can't reach its maximum operating temperature while this is happening. This causes the fuel to remain in the exhaust after combustion is complete, which increases the amount of pollutants. Additionally, fuel consumption rises due to idling [14-19]. Vehicles and engineering machinery rely on diesel engines due to their efficiency. Nevertheless, the after-treatment cost to reduce intrinsic NOx and Particulate Matter (PM) emissions is rising dramatically due to the tightening of laws. In addition, according to the World Energy Council (WEC) [1], the diesel-to-gasoline demand ratio will rise from 1.5 in 2020 to 3.8 in 2040 [20-25].

Without investigating potential substitutes for petroleum diesel, the fuel shortage for diesel engines is only going to worsen. Because of its high oxygen content, similar physical and chemical qualities to petro-diesel, and abundant resources, biodiesel is being considered as a possible alternative to petroleum diesel fuel [2-4]. Renewability is an additional benefit of biodiesel [26-31]. Biodiesel can effectively reduce well-to-wheel CO_2 emissions by 50–80% compared to petroleum diesel, despite some higher energy consumption during manufacturing [5,6]. From a CO_2 emission reduction standpoint, this makes biodiesel an attractive fuel for diesel engines. The manufacture and use of biodiesel have been actively promoted by numerous nations. U.S., Brazilian, and German producers accounted for the vast majority of 2014's 29.7 billion litres of biodiesel [32-41].

Both the US and EU have promised to increase biofuels' share of the market in the future [8]. A national standard for biodiesel was introduced in 2007 by China's National Standards Commission, signalling that the country was also starting to pay attention to the use of biodiesel. Biodiesel combustion, emissions, and performance have been the subject of research at national and international institutes. Research has demonstrated that biodiesel plays a role. Nox emissions rise as hydrocarbon (HC) and carbon monoxide (CO) emissions fall. Brake thermal efficiency typically remains relatively unchanged or even improves somewhat, even though Brake Special Fuel Consumption (BSFC) rises as a result of biodiesel's low heating value. Biodiesel outperforms diesel in engine bench tests when it comes to particulate matter and unburned gaseous emissions. Nevertheless, there are still a few obstacles to overcome when using biodiesel in diesel engines [42-49].

The main issue is the poor low- and low-temperature flow characteristics. The high cloud points of biodiesel fuels might lead to fuel delivery line blockages. The kinematic viscosity of biodiesel fuels is similarly high. Fuel atomization and breakdown are both negatively affected by too high viscosity, which can lower combustion quality and cause issues with engine deposits. In Homogenous Charge Compression Ignition (HCCI) mode, Polyoxymethylene Dimethyl Ethers (PODE) exhibits remarkable combustion stability under lean burn and high Exhaust Gas Recirculation (EGR) circumstances, thanks to its high cetane number and over 50% oxygen content. Low volatility and cloud points are characteristics of PODEs with a degree of polymerization less than 5. Diesel fuel's cloud point and viscosity can be decreased, according to previous research, by adding PODE that has a lower cloud point and viscosity. The addition of PODE to petroleum fuel significantly decreases soot emissions [50-56].

Consequently, there is a larger possibility for decreasing diesel engine emissions by blending PODE and biodiesel, since their physical features can compliment each other. Polymerization processes can be used to create PODEn from methanol [57-65]. The coal chemical industry makes methanol readily available. Since China's coal resource is significantly larger than its oil resource, the country's energy structure might be rationalised by employing PODEn in diesel engines. Wang, Zheng, et al. (2013) created a commercial technique for producing PODEn with a capacity of 30 kt/year. One metric tonne of PODEn requires 1.3 metric tonnes of methanol, and its manufacture costs around $500 per metric ton—making it less expensive than diesel in China. The low-temperature flow characteristics and poor viscosity of biodiesel can be enhanced by blending PODE with it. If a fuel blend of biodiesel and PODE also demonstrated comparable results. As a potential replacement fuel for compression ignition engines in the future, diesel engines provide improved combustion, emission characteristics, and efficiency. Nonetheless, biodiesel/PODE blend fuel has received scant attention from researchers up until this point. In order to create biodiesel/PODE blend fuel, this article mixes PODE with biodiesel. We compare and contrast the engine efficiency, combustion parameters, and pollutant emissions of engines running on petroleum diesel and pure biodiesel with those running on biodiesel/PODE blend fuel [66-72].

A PODE with a low polymerization degree (<5) exhibits minimal volatility and cloud points, as demonstrated in Table 1. Diesel fuel's cloud point and viscosity can be decreased, according to previous research, by adding PODE that has a lower cloud point and viscosity. The addition of PODE to petroleum fuel significantly decreases soot emissions. Consequently, there is a larger possibility for decreasing diesel engine emissions by blending PODE and biodiesel, since their physical features can compliment each other [73-79]. The low-temperature flow characteristics and poor viscosity of biodiesel can be enhanced by blending PODE with it. A potential future alternative fuel for compression ignition engines might be biodiesel/PODE blend fuel, provided it demonstrates comparable or improved combustion, emission characteristics, and efficiency in a diesel engine. Nonetheless, biodiesel/PODE blend fuel has received scant attention from researchers up until this point [80-89]. In order to create biodiesel/PODE blend fuel, this article mixes PODE with biodiesel. We compare and contrast the engine efficiency, combustion parameters, and pollutant emissions of engines running on petroleum diesel and pure biodiesel with those running on biodiesel/PODE blend fuel [90-97].

Literature Review

In their study, Ahmed et al. [1] compared baseline diesel fuel with blends of 10% and 15% ethanol-diesel. They discovered that when applied to a compression ignition engine, the blends resulted in a 27% and 41% reduction in particulate matter (PM), respectively. On the other hand, the blends saw an increase of 4% and 5% in nitrogen oxides (NOx), respectively. In addition, there are a few drawbacks to using ethanol-diesel blends. For example, you'll need an additive to make sure the two fuels mix well, and the mixed fuel isn't very lubricating. To help stabilise ethanol in diesel mixtures, biodiesel could be a useful ingredient. Blends of diesel, biodiesel, and ethanol were investigated for their solubility and emission properties by Kwanchareon [2]. At high engine loads, they discovered that CO and HC were much reduced, while NOx were more than with diesel fuel.

According to Hansen et al. [3], ethanol has the potential to be an efficient addition for decreasing NOx emissions since it lowers the combustion temperature as a result of increased evaporation heat, which in turn reduces NOx emissions. Various sources of biodiesel fuel have different physical and chemical properties, which means they could not always match the standard standards (Rao et al., [4]). Because of its unique composition, biodiesel fuel has the potential to alter the way a diesel engine burns. Because of its greater density and viscosity, biodiesel, for instance, can lead to subpar spray and atomization when injected. The efficiency and pollution levels of Mahua biodiesel mixed with ethanol were investigated by Bhale [5]. Using 20% blended fuel reduced CO and NO emissions, but increased HC emissions, according to their study. Nevertheless, there is a dearth of information regarding the efficacy and emissions of additives such as dimethyl ether when combined with neat biodiesel (B100) made from jatropha oil.

According to Rehman [6], the quantities of nitrogen oxides in emissions rose as the biodiesel content of jatropha oil rose, whereas the concentrations of hydrocarbons and carbon monoxide fell. Further research is needed to determine the impact of antioxidant addition on the combustion parameters of diesel generators when employing biodiesel-diesel blends containing jatropha oil. Biodiesel is known to have worse oxidation stability, a greater cold filter plugging point (CFPP), and higher densities and kinematic viscosities (KV) than diesel, according to Gerpen et al. [7]. (a mixture of paraffinic, naphthenic, and aromatic hydrocarbons). When fuel solidifies at the CFPP, it can clog the fuel filter to the point that the engine stops running. Because of its potential to clog engine fuel lines and filters, biodiesel isn't ideal for usage in colder climes due to its poor low-temperature flow qualities. Density is one of many biodiesel fuel qualities that are related to other metrics, such as heating value and cetane number.

When comparing the fuel attributes of diesel blends with jatropha oil methyl esters (JMEs) at various blending ratios to the biodiesel-diesel blend criteria, such as oxidation stability and CFPP, Chen et al. [8] found some interesting results. It was determined that there were relationships between the fuel attributes of JMEs-diesel blends and the blending ratio of JMEs. Our earlier research indicated that the JMEs might be made more resistant to oxidation by adding the phenolic antioxidant pyrrogallol (PY).

Fuel Preparation and experimental setup

In this study, three different fuels were evaluated: diesel (D100), biodiesel (B100), and a biodiesel/PODE mix fuel containing fifteen percent PODE by volume (B85P15). With a mass distribution of 2.553 percent for PODE2, 88.9 percent for PODE3, and 8.48 percent for PODE4, the PODE was synthesised and separated. Table 2 lists the basic characteristics of the three fuels and PODE that were tested. Figure 1 displays the distillation curves. The boiling range of B85P15 is clearly lower than that of B100, suggesting that biodiesel's volatility can be enhanced by adding PODE. Approximately 15% of B85P15 is oxygen. When the oxygen percentage is less than 15%, our earlier research demonstrated that raising the oxygen content successfully reduced soot emissions. Beyond 15%, however, any increases to the fuel blend's oxygen percentage would have little effect on DS emissions.

Table 1: PODE Properties

Fuel	Density (g/cc)	Cetane number	Oxygen content (%wt)	Lower Heating value(MJ/Kg)
Diesel	0.830	56	0.05	42.68
DME	0.67	55	34.8	27.33
PODE2	0.96	63	45.3	20.32
PODE3	1.02	78	47.1	19.13
PODE4	1.06	90	48.2	18.38
PODE5	1.1	100	49	17.85

The surrounding area has elevated pollution levels. Car companies are working hard to meet the strict emission standards while simultaneously improving the performance and efficiency of their engines. With each passing day, both the demand for and supply of fossil fuels continue to rise. Diesel has substantially greater demand than gasoline in countries like India. Biodiesel is introduced to the market to fulfil this need. It is possible to substitute some of the diesel fuel used in this nation with biodiesel, a renewable fuel made from both new and recycled vegetable oil, which burns reasonably cleanly.

Jatropha Oil

Using industry-standard procedures, we tested diesel with jatropha curcas oil to identify its most salient physical and chemical characteristics. Table 1 displays the findings of the analysis. The findings reveal that vegetable oil has a heating value that is similar to diesel oil, but diesel fuels have a slightly lower cetane number. Diesel oil has a lower flash point and kinematic viscosity than jatropha curcas oil, which is several times greater.

Pretreatment: This process begins with filtering the jatropha oil to remove any solids, then heating it to 110 C for 30 minutes to evaporate any moisture (moisture is responsible for saponification in the reaction). We extracted a tiny amount of usable wax, carbon residue, unsaponifiable material, and fibre after de-moisturizing the oil. We conducted significant experiments on the oil's accessible free fatty acids [98-109].

Esterification: Free fatty acids range from 6% to 20% (wt) in jatropha oil, according to references 13–16. A catalyst is used to facilitate the chemical reaction between jatropha oil and an alcohol (methyl) in order to form the methyl ester. After heating the jatropha crude oil to 50C, half a percent sulfuric acid by weight is added to the oil, followed by thirteen percent methyl alcohol by weight. To hasten the process, methyl alcohol is added in excess. Over the course of 90 minutes, with stirring at 650 rpm and a temperature range of 55–57 C, the reaction was monitored for free fatty acid (FFA) levels every 25–30 minutes. The reaction comes to a halt when the FFA concentration drops below 1% [110-117].

Fuel management, storage, and transportation are all profoundly impacted by the flash point. Storage and transportation of fuels with higher flash points are safer. One significant safety benefit of biodiesel is its 50% higher flash point compared to diesel. Additionally, the flash points of biodiesel-diesel blends are higher than those of regular diesel. According to the reports we looked at, the typical flash point for biodiesel-diesel mixes is at 107.75 Celius [118-124].

One of the major concerns with biodiesel is its lacklustre physicochemical characteristics when exposed to low temperatures, which makes it difficult to thin out jatropha oil, which has a high viscosity (poor low-temperature flow property). In relation to the fuel temperature, cloud point, and pour point, the molecular structure and quantity of saturated fatty acid methyl esters are the primary determinants of the low-temperature flow feature. This quality is particularly crucial in colder regions, where crystals may form and clog fuel lines and filters, causing various difficulties. In addition, as the wax hardens, it forms an emulsion with water on the engine parts' cold surfaces [125-131].

Experiment setup

A four-cylinder common-rail diesel engine was modified into a one-cylinder research engine, which is used as the test engine. A four-cylinder common-rail diesel engine was modified into a one-cylinder research engine, which is used as the test engine. The fuel injectors, intake valves, and exhaust pipes of the first cylinder are deactivated, and it has its own separate fuel delivery system. Details about the powerplant. The engine is outfitted with a research-type Electronic Control Unit (ECU) that enables complimentary and autonomous regulation of injection parameters, including injection pressure, injection number, and injection timing. The engine testing system is illustrated in Figure 2, which is a schematic.

Setting up the engine for operation. The experiment was carried out at a speed of 1600 rpm with five different engine loads: 0.4 MPa, 0.6 MPa, 0.8 MPa, 0.9 MPa, and 1.0 MPa. With an intake temperature of 30 ± 2 Ɗ C, the engine operated in natural aspiration mode without exhaust gas recirculation (EGR). The temperatures of the coolant and lubrication oil were kept at 80 ± 2 ƊC. Injecting the pilot followed the engine's initial plan. Pilot injection pressures and durations at varying loads are referenced on the engine map. To reach the desired load, a small adjustment was made to the primary injection duration [132-137].

If the incoming air is pulsating, the volumetric efficiency diminishes; the surge tank is utilised for continuous flow of air. The surge tank is a solution to this problem. A water-cooled heat exchanger is used to cool the exhaust gas before it is mixed with the fresh intake air. Starting the LTC mode with the EGR.

The AVL Di-gas analyzer 444 was used to measure the engine's exhaust emissions. In particular, it tracks HC, CO, NOx, O2, and CO2. The emissions are measured by inserting a gas analyzer probe into the exhaust pipe. The emission level and smoke intensity were measured using two different sampling probes that were inserted into the engine to collect exhaust gas samples. We took smoke samples from the engine using filter paper with a diameter of 50 mm. The temperature of the exhaust gas was measured using a K-type thermocouple and a temperature indicator. The cylinder pressure was monitored using a water-cooled Kistler (601A) transducer.

Table 2: Engine Specification

Cooling system	Air
Displacement	662 cm3
Stroke	110 mm
Bore	87.5 mm
Compression ratio	17.5:1
Injection pressure	200 bar
Injection timing	23 Btdc
Rated output	4.4kw at 1500 rpm
Rated speed	1500 rpm

The engine's power output was measured using the electrical dynamometer. It works by changing the strength of the field, which is based on the reaction principle. An electrical instrument must be used to measure the generator's output, and the output's magnitude must be adjusted to account for the generator's efficiency.

Result and Discussion

At fourteen minutes before the top dead centre, the pilot injection takes place (BTDC). A minor amount of heat is released initially, followed by the main discharge. The pilot injection fuel amount is tiny at low load, and the cylinder temperature and pressure are relatively low when it occurs. As a result, the fuel is blended before combustion, and the mixture is rather lean. Fuel chemical reactivity dominates the beginning of combustion under lean-burn circumstances. Among the fuels tested, D100 had the best cetane number, heating value, and pilot combustion heat release rates. A low heating value is preferable for late ignition and low heat release rates, while a high cetane number is preferable for early combustion.

To summarise, when comparing B100 with B85P15, the former shows a little earlier pilot combustion and a comparable peak pilot heat release rate. It is possible for fuel mixes closer to the injector to be more mixed than those further downstream [43]. During the pilot combustion, the mixture may not burn well due to being too lean near the injector. Due to its high viscosity, biodiesel retards over-mixing close to the pilot injection injector, allowing for more efficient combustion in that area. Hence, B100 and B85P15 might have a reactive hot environment that is on par with or better than D100 close to the injector, but having a lower global pilot heat emission. Consequently, at 0.4 MPa IMEP, the three fuels begin their major burning in very similar ways. All three fuels have very similar primary heat release geometries. The peak of the heat release rate shows a small variation (marked by a circle). The main heat release rate is highest for D100 because of its low viscosity. The addition of low-viscosity PODE enhances air-fuel premixing, resulting in a greater main combustion rate for B85P15 compared to B100 (Figure 1).

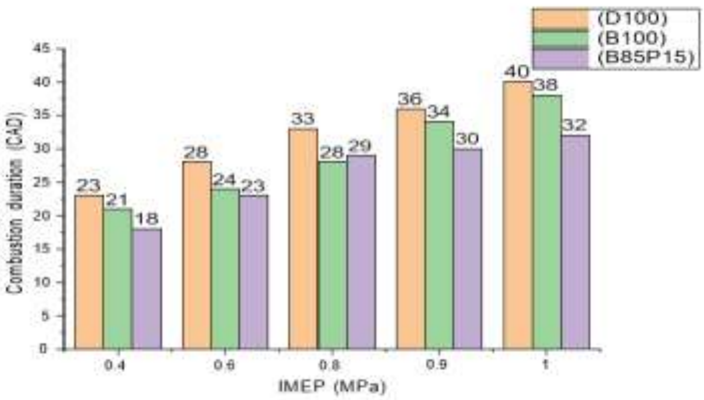

Figure 1: Combustion duration at various loads.

It displays emissions of soot and NOx under different loads. All three fuels produce comparable amounts of soot when operating at low loads. Previous study has demonstrated that using B100 significantly reduces soot at high loads [44,45]. The combination of B100's high oxygen content and its lack of aromatics results in very low soot emissions. PODE outperforms biodiesel and its molecular structure in terms of oxygen concentration.

Combustion of the fuel and air is made easier by the mixture's low viscosity. For this reason, PODE offers greater benefits when it comes to reducing soot. Under heavy load, B85P15 produces significantly less soot than B100, according to the results. When subjected to a load of 0.4 MPa, B100 and B85P15 produce somewhat less NOx than D100 does under higher loads. For all fuels, air is more than enough at low loads. There is no CAC bond in PODE. Another way to establish this effect is to compare the NOx values from the B85P15 and B100 examples. During the load sweep, the three fuels typically produce equal amounts of nitrogen oxides (Figure 2).

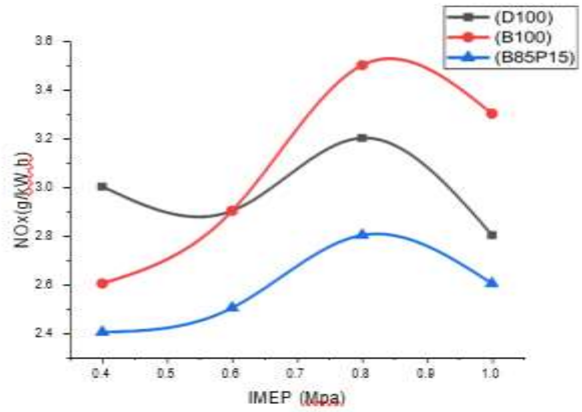

Figure 2: Nox emissions at various loads.

Diesel Particulate Filters (DPFs) are required to achieve the soot objective since, under high load, D100's soot emissions are significantly greater than the acceptable value. Despite a significant decrease compared to D100, the soot emissions for B100 still fall short of the target. During the load sweep, only B85P15 achieves soot emissions that are close to or below the target. As a result, compared to D100, B85P15 may save a DPF and yet meet Euro VI emission requirements (Figure 4).

All three fuels produce nearly identical levels of HC emissions. Combustion temperature rises with increasing load, reducing HC and CO emissions. It is possible that the low cetane number explains why B100 produces a lot of CO at low loads. When compared to B100, B85P15 produces 20% less CO emissions at 0.4 MPa IMEP. When compared to B100, B85P15 produces 20% less CO emissions at 0.4 MPa IMEP. Oxygen becomes inadequate and D100 produces its maximum CO emissions when engine load surpasses 0.8 MPa IMEP. Reduced CO emissions and lean-oxygen zones are possible because to B100's oxygen content. Biodiesel's CO emissions can be further reduced by adding PODE, which has a lower volatility and an even higher oxygen content. Compared to B100, B85P15 produces 36% less CO emissions at 1.0 MPa IMEP.

Combustion efficiency typically improves as engine load increases. During the load sweep, the combustion efficiency of B85P15, D100, and B100 is comparable. Combustion efficiency is marginally worse at low loads for B100 and somewhat worse at high loads for D100. Heat release phasing is delayed at high load, therefore the peak ITE happens at 0.4-0.6 MPa IMEP. The ITE of the B100 is greater under heavy loads but lower under light ones when compared to the D100. Because of its very efficient combustion and very short combustion period, B85P15 achieves the maximum ITE during the load sweep. Combustion of the fuel and air is made easier by the mixture's low viscosity. For this reason, PODE offers greater benefits when it comes to reducing soot. Under heavy load, B85P15 produces significantly less soot than B100, according to the results. When subjected to a load of 0.4 MPa, B100 and B85P15 produce somewhat less NOx than D100 does under higher loads. For all fuels, air is more than enough at low loads. The premixed combustion rate and peak combustion temperature of D100 are both higher. Diesel Particulate Filters (DPFs) are required to achieve the soot objective since, under high load, D100's soot emissions are significantly greater than the acceptable value. Despite a significant decrease compared to D100, the soot emissions for B100 still fall short of the target. During the load sweep, only B85P15 achieves soot emissions that are close to or below the target.

Conclusion

The biodiesel/PODE blend fuel is created by mixing PODE with biodiesel (B85P15). We compare B85P15 to pure biodiesel and petroleum diesel (D100) in terms of engine efficiency, pollution emissions, and combustion characteristics (B100). Using B100 and B85P15, the engine runs well. Compared to D100, B100 and B85P15 have no discernible effect on the engine's ignition delay or combustion phasing. At low loads, all three fuels release heat at about the same rate; but, at high loads, B100 and B85P15 release more heat than D100 does through diffusion combustion. At heavy load, B85P15's total combustion duration is 5 CAD lower than D100's. B100 produces less soot when operating at high load in comparison to D100. An additional 50% reduction in soot emissions is possible with the addition of PODE. B85P15 shows soot emissions of approximately or significantly less than 0.01 g/kW.h during the load sweep. Combustion efficiency is lower at low loads for D100 and higher for B100. During the load sweep, B85P15 has the greatest ITE. The ITE of the B100 is greater under heavy loads but lower under light ones when compared to the D100.

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