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Original Article

Investigation of the Performance and Emissions of a Single-Cylinder Diesel Engine Fueled with Mahua Pyro Oil Mixtures Using ETBE as an Oxygenated Additive

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Abstract - *To lower engine tailpipe emissions, diesel fuel can be oxygenated. This study examines how adding ETBE to Mahua Pyro Oil (MPO25) mixes changes diesel oil's physicochemical properties. ETBE was added in the volumetric ratios of 10%, 15%, and 20%, and the fuel mixtures are designated as MPO25ET10, MPO25ET15, and MPO25ET20, respectively. Adding ETBE to the mixtures affects density, increases the cetane number, and decreases viscosity. The assessment was made on a single-cylinder compression-ignition engine, emission levels of Nitrogen Oxides (NOx), Hydrocarbons (HC) and Carbon Monoxide (CO). Also, performance indicators on brake-specific fuel consumption and brake thermal efficiency were measured. Regarding MPO25 mixtures, results demonstrated that the BTE of an MPO25/diesel blend with 15% ETBE was similar; however, BSFC was somewhat higher. As the NO x releases raised at peak power, HC, smoke exhaust and CO were diminished. Employing just 20% ETBE significantly reduces smoke opacity emissions by 48%, with a 16% increase in NOx emissions.*

Keywords - *Mahua Pyro Oil, Ethyl Tert-Butyl Ether (ETBE), Oxygenated additive, Performance.*

1. Introduction

Due to their greater efficiency compared to gasoline engines, diesel engines are extensively employed in heavy-duty buses, trucks and equipment used in agriculture and mining. Diesel engines produce a lot of unhealthy substances in the air, including CO, NOx, UBHCs, PM, and smoke. Although diesel engines offer numerous operational benefits, their emissions of gas pollutants and particulate matter pose a significant threat to global warming [1, 2]. Diesel engines have to find new fuels since traditional fossil fuels are being used up too quickly and because of the worries over the greenhouse gas emissions they produce [3, 4]. When used in compression ignition, vegetable oils demonstrate comparable combustion properties and performance to petroleum diesel, making them a potential substitute for fossil fuel.

Compared to diesel fuel, vegetable oil has lower volatility, poor flow at low temperatures, higher density, and higher viscosity. Valve seats and coking injector nozzles, Contamination of lubricant oil, stuck piston rings, pitiable fuel atomisation, clogged fuel filters, and greater NOx discharges are some engine durability difficulties induced by long-term vegetable oil use [5, 6].

Diesel engines can run on biodiesel either straight from the source or a mixture of vegetable, animal and waste fuels, which can made in a certain ratio [7, 8]. Due to its low cost, high cetane number, lubricant feature, low flash point, and less hazardous exhaust emissions, biofuel is a choice for diesel fuel. Since its low cost, high cetane number, lubricating feature, low flash point, and less harmful exhaust emissions, biodiesel is excellent [9, 10]. When compared to diesel, biodiesels have superior combustion properties. Biodiesel reduced CO and HC emissions the greatest associated with the other biodiesel blends evaluated; however, it increased NOx emissions [11, 12]. Chauhan [13] found that a Jatropha biodiesel-powered CI engine released less pollution, except NOx. [14] found that pure pine methyl ester reduced HC, CO, and smoke releases in the engine employing pine oil blends with diesel.

Alternatively, oxygenated compounds can reduce particle emissions [15]. Oxygenated chemicals minimise particle emissions, although diesel's molecular structure and oxygen level determine their effectiveness [16]. Diesel chemical composition and additives affect density, volatility, viscosity, Cetane Number (CN) and low-temperature behavior. However, diesel/ethanol mixtures increase UBHCs and aldehydes [17-19]. Ethanol significantly reduces cetane number, viscosity, and combustion heat in fossil fuels [20, 21].

Common oxygenated additives like DMM, DMC, Ethylene Glycol Monoacetate, ETB, MEA, Diglyme, and ETBE have been tested for their ability to reduce exhaust emissions and improve anti-wear [22]. Ethyl-Tert-Butyl Ether (ETBE), made of isobutane and ethanol, is another diesel oil oxygenate. [23] found that adding ETBE to diesel oil dramatically changes volatility (including flashpoint and purification curve), viscosity and cetane number, degrading fuel performance. [24] examined diesel engine smoke emissions and PM with ETBE supplementation. PM emissions can be reduced by 36% using 10% ETBE. At 1400 rpm and 80 N m, a 40% ETBE fraction reduced smoke opacity by 70%.

ETBE integration into diesel fuel affects combustion features and emissions of a CRDI diesel engine with high-cooled EGR. Associated with pure diesel, the 30% fuel mix of ETBE widens the operational load range for ultra-low NOx, smokeless and competent combustion with higher cooled EGR rates [25]. Adding ETBE to diesel fuel, as with ethanol [26], may enhance uncontrolled hazardous emissions such as aldehyde or carbonyl. However, little research has examined ETBE as a diesel fuel additive [27]. ETBE should be studied to see how it impacts diesel engine features and emissions before it is extensively utilised.

The purpose of this research is to investigate the impact of adding (ETBE) to Mahua Pyro Oil (MPO25) blends on the physio-chemical properties, performance, and tailpipe emissions of a single-cylinder CI engine. The study aims to optimize the ETBE blending ratio to achieve enhanced BTE while minimizing emissions such as HC, CO, and smoke opacity. Additionally, the research seeks to analyze the trade-off between improved combustion characteristics and the potential rise in (NOx) emissions due to oxygenation.

2. Materials and Methods

2.1. Creation of Mahua Pyro Oil

Figure 1 shows quick, semi-batch pyrolysis to produce mahua oil. The pyrolysis system used a stainless-steel semi-batch reactor. First, raw components were heated in a semi-batch halt to the pyrolysis reactor with a fine PID controller. The reactor temperatures were raised to 20°C each minute from 450 to 600°C.

Nitrogen gas was presented into the reactor to maintain an inactive atmosphere during each run. Following the volatilization of substances, non-condense gases were discharged into the atmosphere via a water-cooled condenser. Subsequently, the liquid product was separated into aqueous and oil phases. Further physical and chemical characterization of both products revealed their potential as substitutes for diesel fuel. The color of neat Mahua oil is depicted in Figure 1. Chemical analyses designated a higher proportion of aliphatic compounds in the bio-oil compared to aromatics. These oil characteristics were assessed at the ETA Lab in Chennai.

The physio-chemical characteristics of fuels were compared and documented in Table 1. This comprehensive approach to production and characterization underscores the feasibility of Mahua oil as a maintainable alternative to traditional diesel fuels, offering promising prospects for renewable energy sources and environmental conservation efforts.

2.2. Experimental Engine Set-Up

Figure 2 shows a Kirloskar engine tested using an eddy current dynamometer. We used a centrifugal governor to control engine speed by applying loads and regulating electrical currents to induce shaft impedance. Table 2 lists engine specs.

Diesel and biodiesel were stored in separate tanks, and fuel usage was assessed by the burette and stopwatch time it took the engine to burn 10 cc. Engine temperature was monitored using a Chromel Alumel (K-Type) thermocouple with a 0-500°C range. A gas analyser measured NO, HC, and CO emissions, while an AVL smoke meter measured smoke opacity.

The head of the cylinder also has a KISTLER piezoelectric pressure sensor to reduce passage effects. Crank angle encoders tracked the engine's combustion pressure- CA history, and an elect -optical sensor located TDC. A high-speed automatic data collection system collected cylinder pressure, TDC position and crank angle. To guarantee data quality and consistency, signals were gathered and examined throughout 100 successive cycles.

Engine power and emissions were measured every five minutes for each fuel and load condition. Means of three runs were recorded for each experiment set, encompassing parameters for performance evaluation, emissions, and smoke opacity. This comprehensive testing methodology facilitated a thorough analysis, providing valuable insights for optimization and improvement strategies.

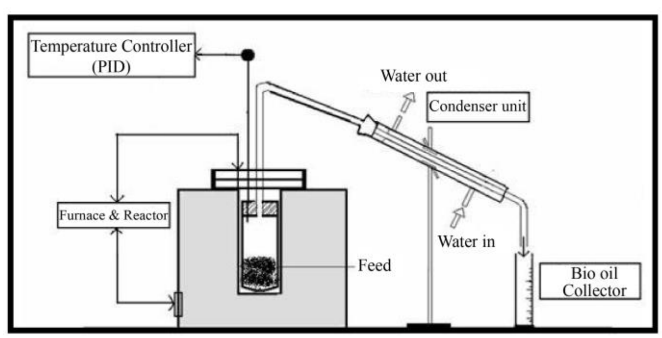

Fig. 1 Pyrolysis setup

Table 1. Mahua and ETBE fuels with ASTM

Properties	Diesel	Mahua Pyro Oil	ETBE
Density @ 20 °C (kg/m3)	833	921	747
Kine. Viscosity @ 40 °C (cSt)	2.7	23.19	-
LCV(MJ/kg)	43	39	37.9
Latent Heat (°C)	270	240	309
Cetane number	47	38	8
Flash point	54	184	-
Stoichiometric air–fuel ratio	15	13	12
Carbon (wt%)	86.1	-	70.5
Hydrogen (wt%)	13.8	-	13.8
Oxygen (Mass ppm)	-	<1	15.7
Nitrogen (Mass ppm)	>1	>1	0
Sulphur (Mass ppm)	3	0	0

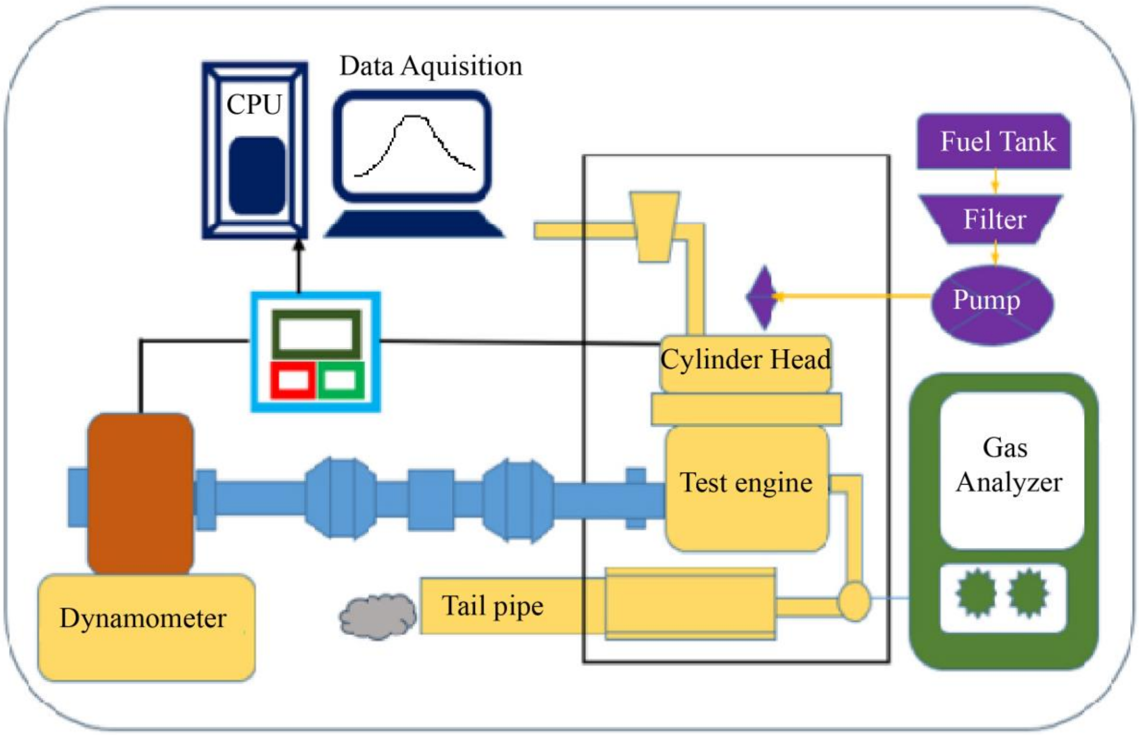

Fig. 2 Representation of test engine set-up

Table 2. Test engine technical details

Make	Kirloskar, Vertical, 4S
Inject. Pressure (bar)	200
Speed (rpm)	1500
Power (kW)	4.4
Inject. Timing (°C)	23obTDC
Bore (mm)	87.5
Comp. Ratio	17.5:1
Stroke (mm)	110

Additionally, a KISTLER piezoelectric pressure sensor remained installed inside the cylinder head to mitigate passage belongings. Crank angle encoders monitored the engine's combustion pressurized crank angle past, while an electro-optical sensor identified the Top Dead Centre (TDC) position. Data about CP, CA, and TDC positions were gathered utilising a high-speed automated data gathering system. To guarantee data quality and consistency, signals were gathered and examined throughout 100 successive cycles. Engine power and emissions were measured every five minutes for each fuel and load condition. Means of three runs were recorded for each experiment set, encompassing parameters for performance evaluation, emissions, and smoke opacity. This comprehensive testing methodology facilitated a thorough analysis of engine performance and emissions under various operating conditions, providing valuable insights for optimization and improvement strategies.

3. Results and Discussion

3.1. Pressure-CA Diagram

Figure 3 depicts diesel and MPO25 with ETB mixes' crank angle-dependent cylinder pressure. Higher viscosity and lower peak energy content give MPO25 a lower peak cylinder pressure than diesel. At max load, diesel and MPO25 blend have 68 bar and 65.4 bar peak cylinder pressures, while MPO25ETBE20, MPO25ETB15, and MPO25ETB20 have 65 bar, 67 bar, and 64.5 bar.

Compared to MPO25 mix at peak load, MPO25 with 15% ETB blends increases by 1 bar and decreases by 1 bar and 1.5 bar for 10%ETB and 20%ETB blends. Higher ETB blends may lower cylinder pressure because butanol's high latent heat lowers the temperature of the charge at peak load, lowering high pressure.

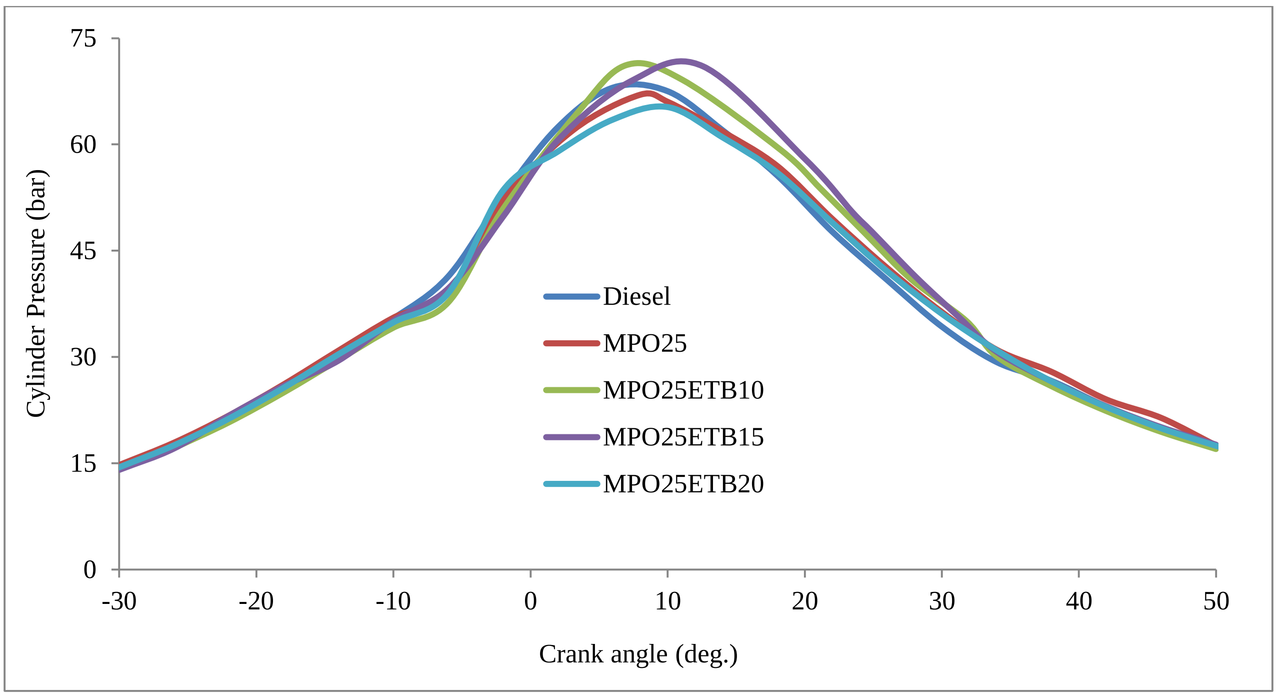

Fig. 3 CP variations with CA

3.2. Heat Release Rate

Figure 4 shows diesel, MPO25, and ETB HRR change with CA. The shorter ignition delay for MPO25 with ETB blends increases the premixed combustion phase compared to the MPO25 blend at peak load. MPO25 with 10%, 15%, and 20% ETB mixes releases 57J/ºCA, 61J/ºCA, and 62J/ºCA at full load, while diesel and MPO25 release 63J and 60J. Since ETB improves biodiesel ignition, it may have enhanced the premixed combustion phase and HRR for MPO25-ETB20 blends.

3.3. BTE

The BTE, or converting fuels efficiency, shows how well fuel chemical energy is converted into mechanical effort. BTE/BP fluctuation for diesel and MPO25/ETBE combinations is seen in Figure 5. High viscosity and density make MPO25's BTE lower than diesel at various loadings, resulting in low atomisation and lower biodiesel energy content. Due to biodiesel combustion improvements, ETBE increases BTE by 20% in MPO25.

Due to its increased flammability, ETB may react faster with air and fuel to form a similar mixture, improving combustion and BTE. The BTE for diesel and MPO25 is 30.4% and 28.7% at maximum load, while MPO25ETB15, MPO25ETB20, and MPO25ETB10 are 29.6%, 28.2%, and 27.8%. ETBE's high oxygen content may improve combustion, causing BTE to rise. More complete fuel combustion enhances engine thermal efficiency.

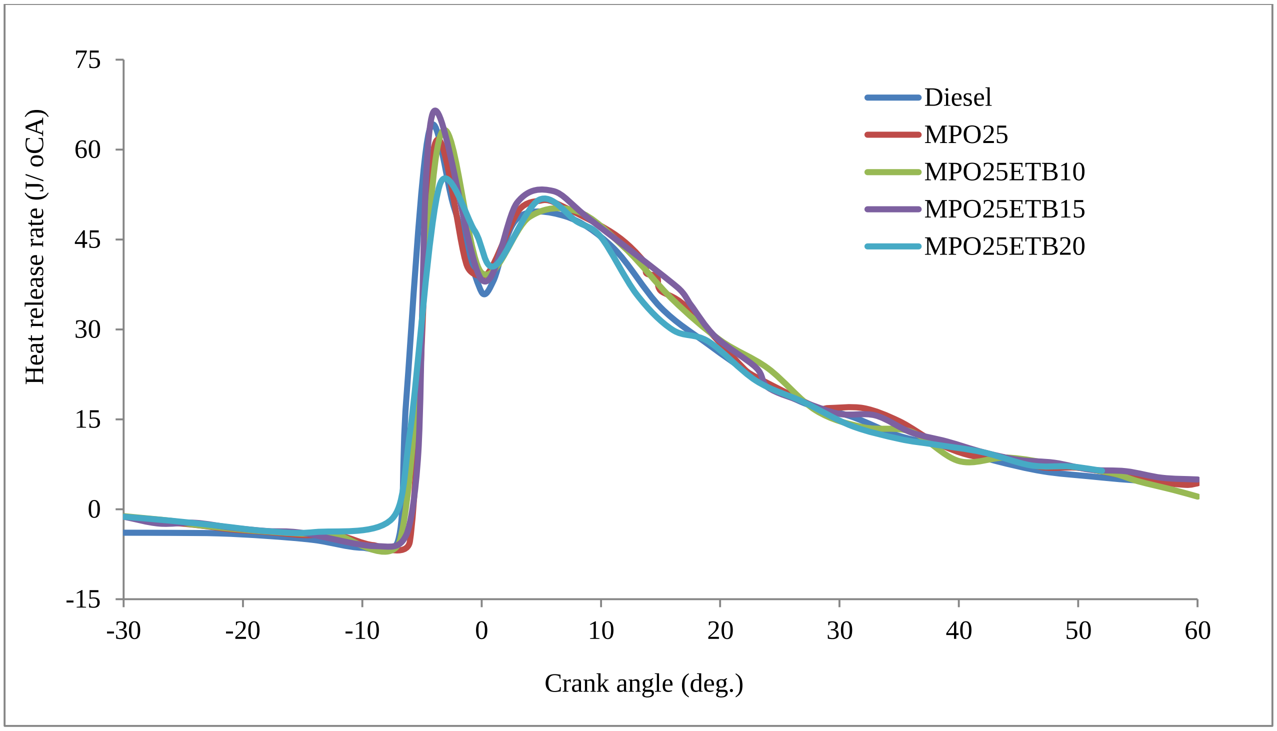

Fig. 4 HRR variations with CA

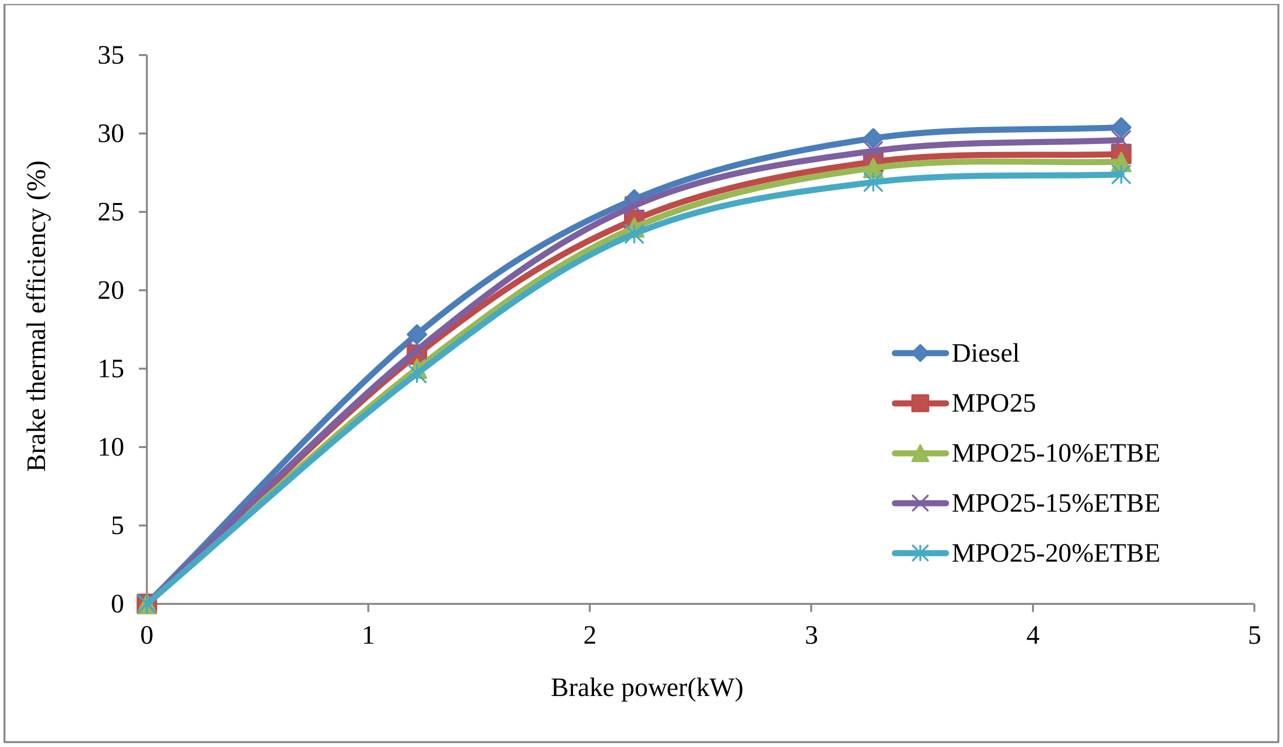

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Fig. 5 BTE versus BP

3.4. Brake-Specific Fuel Consumption

BSFC with BP for diesel and MPO25 with ETB mix changes in Figure 6. ETB increases fuel cetane number, shortening ignition delay and smoothing combustion. Diesel and MPO25 have BSFCs of 0.28 and 0.31 kg/kWh at maximum load, while MPO25 with 20%, 15%, and 10% ETB mixes have 0.3, 0.315, and 0.334 kg/kWh. MPO25 with 20%ETB has a lower BSFC than MPO25 without ETB mix due to the ETB's higher oxygen and strong ignition properties, which increase combustion.

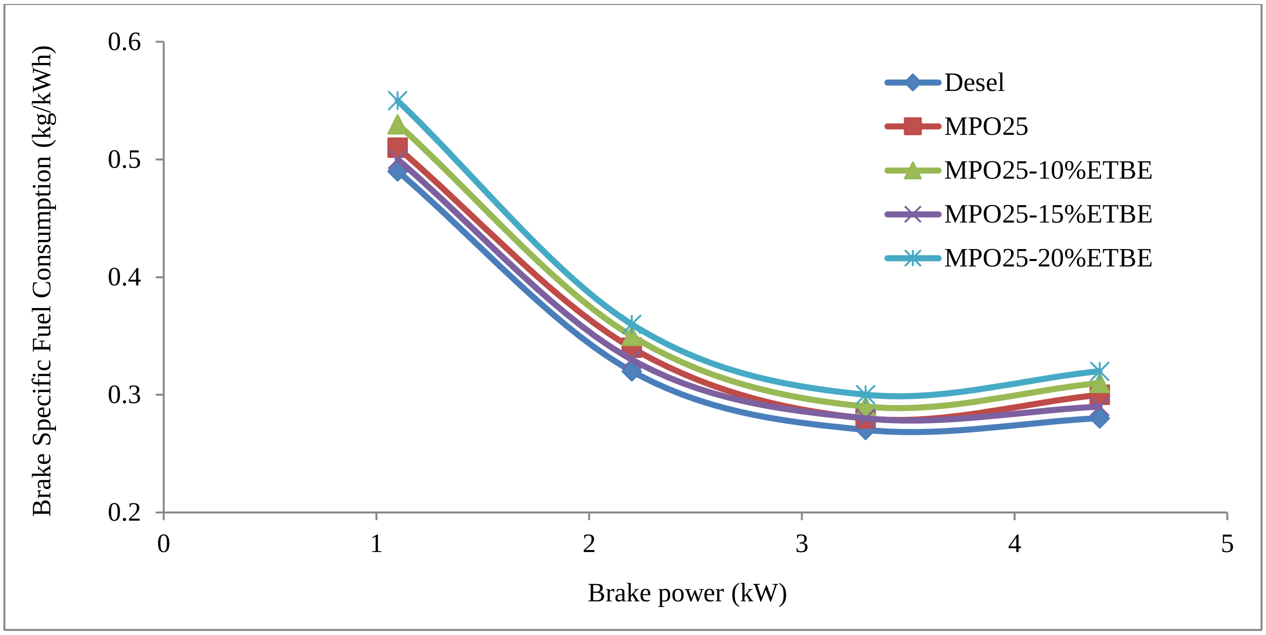

Fig. 6 BSFC versus BP

3.5. Exhaust Gas Temperature

EGT and BP fluctuations for diesel and MPO25/ETB blends are seen in Figure 7. The EGT rose as the load rose because large fuel was needed to generate power. MPO25 and diesel EGT have declined, as have ETB additives relative to diesel fuel. Full-load diesel and ETB20 EGTs are 362°C and 385°C, respectively. MPO25 with 10%, 15%, and 20% ETB mixes reached 368°C, 338°C, and 324°C at full load. ETB's faster combustion and latent heat of vaporisation characteristic may have lowered exhaust gas temperature by cooling charges and lowering peak combustion temperature.

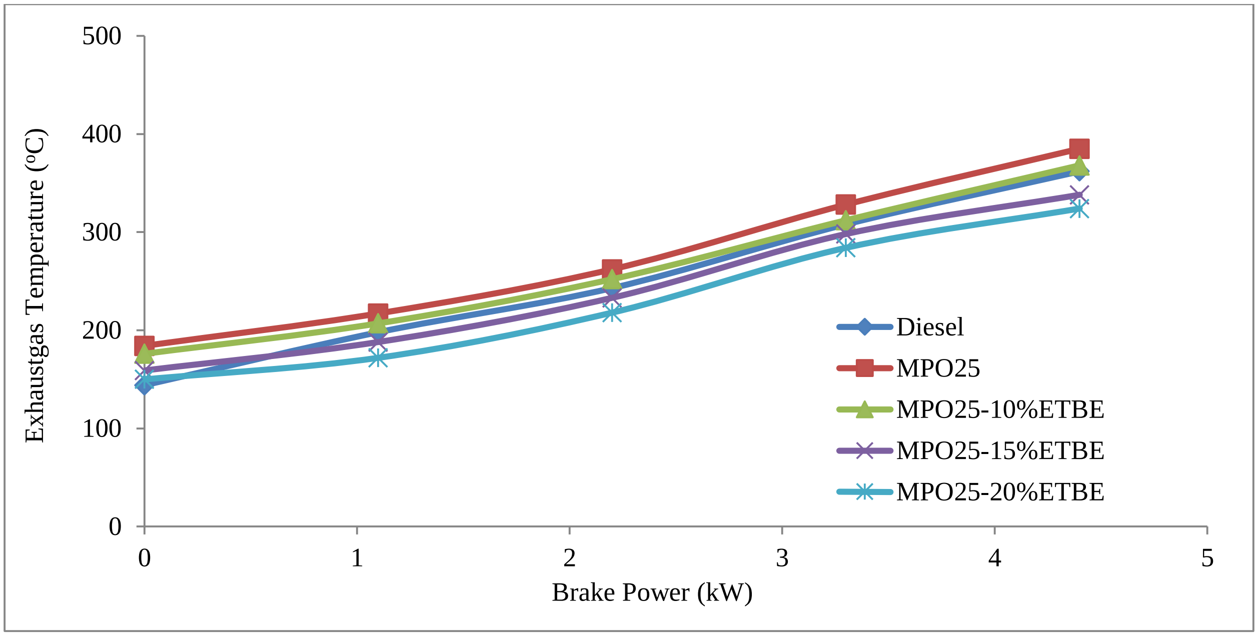

Fig. 7 EGT versus BP

3.6. Carbon Monoxide Emission

Figure 8 depicts the change in CO exhausts with diesel BP and MPO25 with ETB mixes. CO discharges occur in rich air-fuel mixture locations due to an inadequate oxygen supply. CO emissions for MPO25 are less than diesel at all loading conditions because of the intrinsic O2 molecule included in the biodiesel structure, which improves fuel oxidation and results in reduced CO emissions. The addition of ETB to

MPO25, in particular, reduces CO because it increases cetane number, which enhances the mixture combustion. CO emissions of MPO25 are 0.12%, MPO25ETBE20 is 0.15%, MPO25ETB15 is 0.16%, and MPO25ETB20 is 0.18%, respectively, while diesel emissions are 0.14% at peak load. The consequent reduction in CO emissions, along with the existence of additional O2 in the structure, promotes full combustion.

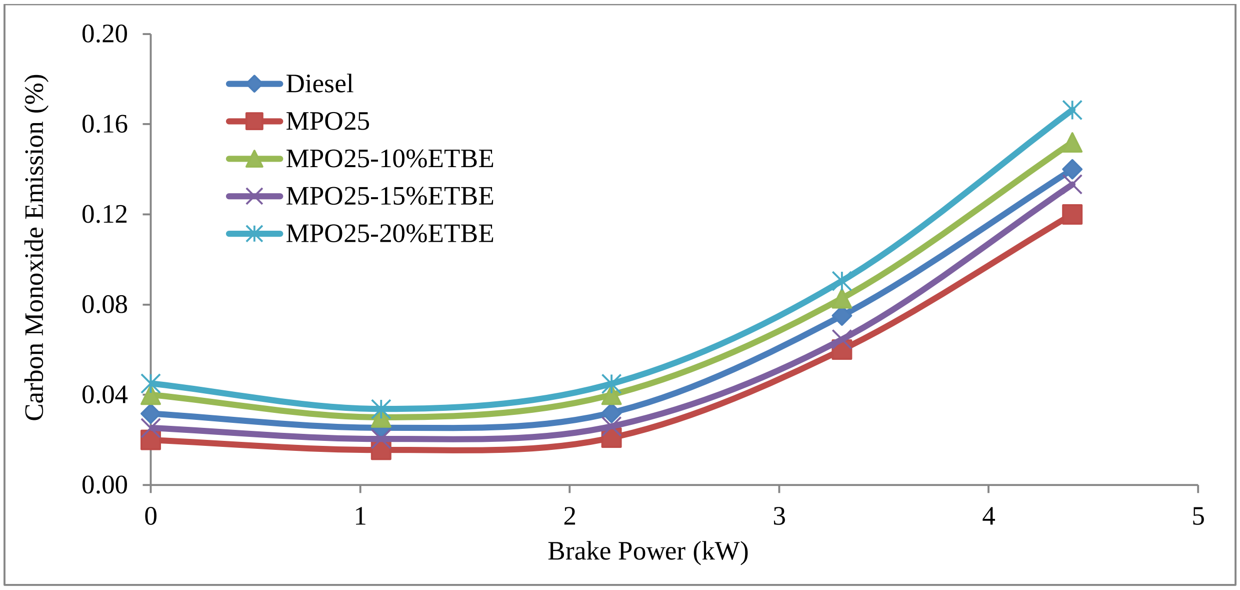

Fig. 8 CO emission versus BP

3.7. Hydrocarbon Emission

Figure 9 depicts the variance in HC discharge with BP for diesel and MPO25 with ETB mix fuels. Flame quenching at the cylinder walls and gaps in ring grooves are responsible for the development of increased HC emissions. However, MPO25 with ETB blends resulted in a drop in the HC exhaust pattern at all loadings of the ETB mix. At max load, the HC release for diesel and MPO25 are 26 ppm and 32 ppm; correspondingly, for MPO25 with 10%, 15%, and 20% butanol blends-25 ppm, 28 ppm, and 34 ppm. The culprit is high cetane additive, which diminishes the time existing for mixing air and gasoline. As an outcome, premixed combustion minimizes the length of combustion while increasing the duration of diffusion combustion. Notably, a heterogeneous air-fuel combination creates more HC during diffusion combustion. Also, the drop in HC emission for ETB blends is attributed to the ETB mixture's shorter ignition latency.

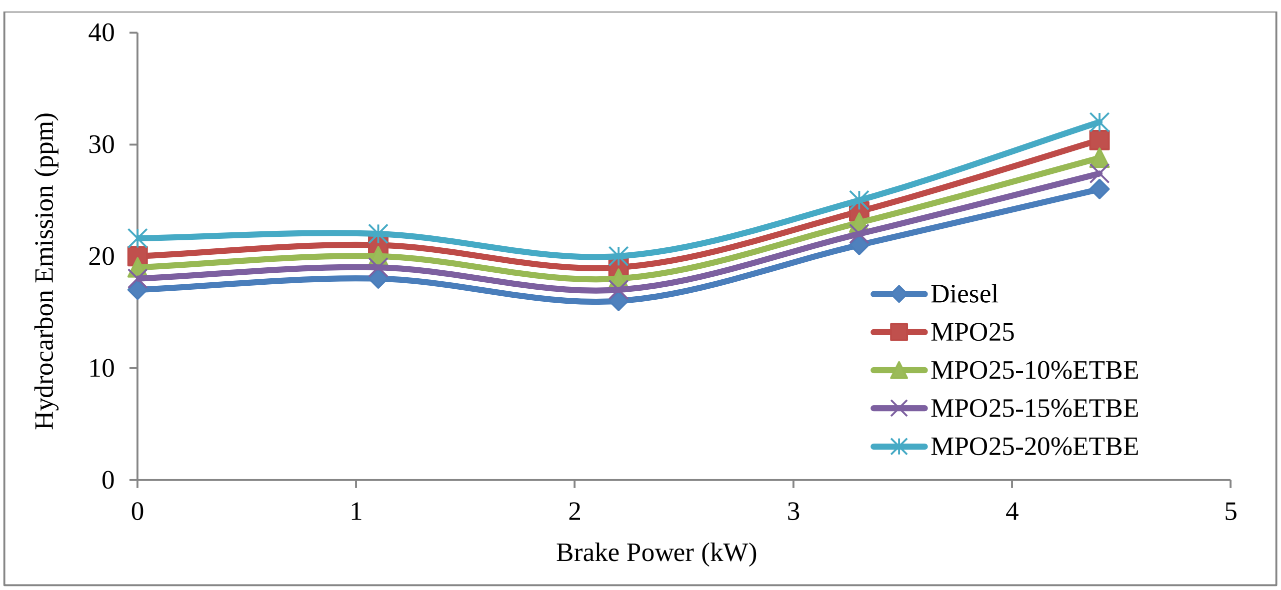

Fig. 9 HC emission versus BP

3.8. Nitrogen Oxide Emission

Figure 10 illustrates the variation in NO discharge with BP for diesel and MPO25 - ETB mixes. In general, NOx emission is dominated by the biodiesel mixture's maximum burning temperature and O2 levels. The addition of ETBE in biodiesel facilitates even fuel circulation and lessens premixed combustion. As an outcome, emissions of NO decreased for ETBE fuel blended with MPO25 at peak load. The addition of ETBE with MPO25 increases the NO emission and the increases in ETBE blend with MPO25. At peak load, NO emissions for MPO25 are 1037ppm, 866ppm for MPO25ETB10, 1186ppm for MPO25ETB15, and 1256ppm for MPO25ETB20, whereas diesel and MPO25 are 1040ppm and 1105ppm, respectively.

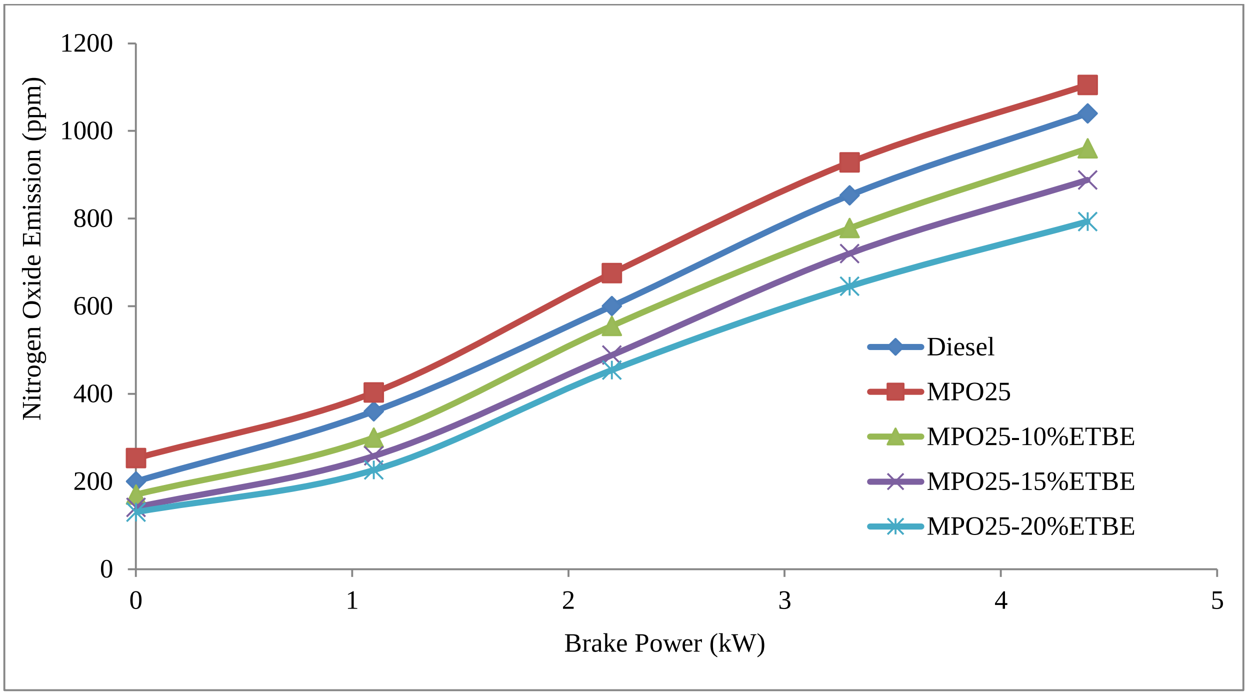

Fig. 10 NO emission versus BP

3.9. Smoke Opacity

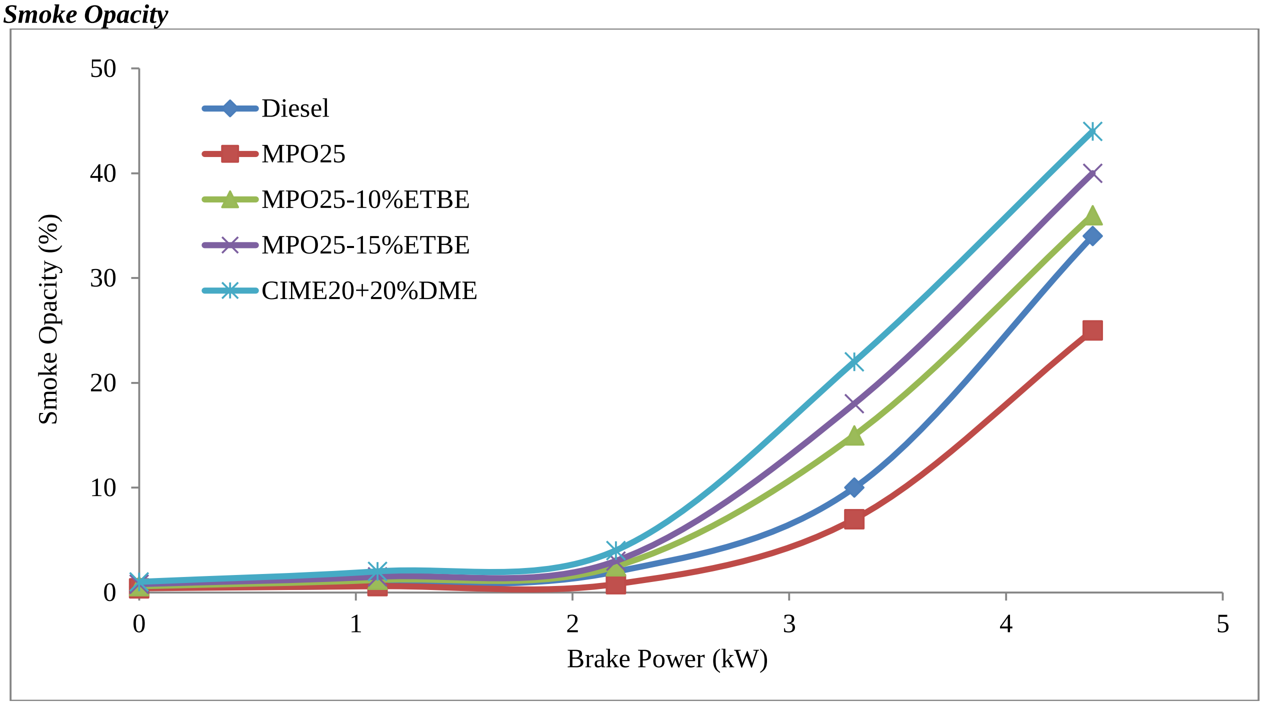

Fig. 11 Smoke opacity emission versus BP

The engine ran at full load with 1500 rpm to quantify smoke emissions. The variety of diesel's smoke opacity and ETBE mix for diesel and MPO25 with different magnitudes of mixtures is depicted in Figure 11. On inference, diesel generates the maximum amount of smoke emissions. At the same time, biodiesel delivers minimum smoke, which can be due to the fact that MPO25 is rich in oxygen content that helps its oxidation and decreases its smoke emissions. Adding ETBE with biodiesel blends especially lowers opacity emission by up to 20% ETBE blends. The figure clearly showed that compared to diesel, adding 10%, 15%, or 20% ETBE reduced smoke opacity by 17%, 33%, and 44% at maximum power, respectively, compared to MPO25. The smoke opacity was lowered by 44% when using higher volume fractions of 20% ETBE. Smoke opacity of MPO25ET10, MPO25ET15 and MPO25ET20 is 28%, 24% and 18%, respectively, but for diesel and MPO25 is 34% and 32%, respectively, at max load.

4. Conclusion

This study examined how a diesel-biodiesel blend with ethyl tert-butyl ethers affected the emissions and combustion of a single-cylinder CI diesel engine. Comparisons were made with diesel-bio-oil results. The research led to these conclusions:

- ETBE mixes improved combustion for all fuels. The in-CP and maximum HRR increased with ETBE combinations.
- Adding oxygenate ETBE20 to MPO25 enhanced the BTE compared to MPO25, but still lower than pure diesel, but higher than MPO25, with an average increase ranging from 0.5% to 0.9%. BSFC was decreased for MPO25ETBE15 by 3.3%, and other blends were increased at peak power.
- Using oxygenate ETBE20 with MPO25 at peak load has an average increase in HC and CO emissions of 8-42%, and 6%-10%, respectively, compared to MO25. At peak powers, MPO25ETBE20 reduced NOx by 15-30% and increased smoke by 7-14%.
- It is concluded that MPO25ETBE15 gave better combustion, better BTE and reduced emissions.

4.1. Future Work

The effects of several biofuels and oxygenated additives other than ETBE, such as DME, DEE, or alternative ethers, to assess their synergistic impact on combustion and engine characteristics. Furthermore, it would be beneficial to investigate the long-term durability effects of these blends on engine components and optimize blend ratios for better trade-offs between NOx and smoke emissions.

Acknowledgments

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