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Combustion Performance and Emission Characteristics of Diesel Engine with Neem Oil Methyl Ester and its Diesel Blends

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Abstract:

This research aims to enhance engine performance and reduce emissions by applying Thermal Barrier Coating (TBC) on the piston crown and valves of a diesel engine using both diesel and Neem Methyl Ester (MME) as fuels. A Direct Injection (DI) conventional diesel engine was converted to a Low Heat Rejection (LHR) engine by applying 0.5 mm thickness of 3Al2O3-2SiO2 (as TBC) onto the piston crown and valves, with MME used as the fuel. The fuel injector pressure was maintained at 200 bar for investigation.

Results indicate that the application of TBC increased brake thermal efficiency to 13.65% at 25% load with diesel compared to a conventional DI diesel engine. A significant improvement in specific fuel consumption and brake thermal efficiency of the LHR engine with MME fuel was observed at full load. Using MME and diesel fuels with TBC achieved lower exhaust gas temperatures. Additionally, the smoke density of MME with and without TBC was significantly reduced. Carbon monoxide emissions were moderately reduced under all loads by using MME fuel with TBC. Furthermore, MME with TBC significantly reduced hydrocarbon emissions at all loads.

Keywords: *Neem Methyl Ester biodiesel*, *Diesel fuel*, *Thermal barrier coating*, *Low heat rejection engine.*

1. Introduction:

Biodiesel, a renewable fuel, is non-toxic and biodegradable. It is oxygenated with ester-based fuel obtained from first-generation oils, second-generation oils, and third-generation oils. Biodiesel is formed by a simple chemical reaction between edible or non-edible oils with an acid-base catalyst and alcohols. Biodiesel typically contains around 9% to 12% oxygen content by weight basis and exhibits good lubricity properties.

Sulphur content, and mixability with petro-diesel fuel with various blends of propagation. Thus, biodiesel has a greater impact than petro-diesel fuels [1]. In India, the production of non-edible oils is limited, prompting the government to undertake developmental efforts to produce biodiesel from sources such as Neem, Jatropha, Karanja, Linseed, Cotton, Mustard, etc. In India, most of the states have tribal regions where Neem seeds are found profusely [2]. The Neem tree starts yielding seeds from the 7th year of plantation. Neem seed oil is a common ingredient in Indian hydrogenated fat. Neem raw oil, extracted from the seed kernels, resembles semi-solid fat at room temperature, appearing pale yellow due to the high viscosity. Neem raw oil's free acids contain around 30% to 40% [3]. During the production of biodiesel, various by-products can be obtained from glycerin [4].

Generally, raw Neem oil contains a high percentage of Free Fatty Acids (FFA), and converting FFA to biodiesel is essential through transesterification or esterification processes [5]. Neem oil's properties and chemical composition are similar to other inedible oils such as Cotton, Neem, Karanja, etc., but Neem oil has a higher viscosity and FFA content. Various processes like transesterification, esterification, dilution, micro-emulsion, and pyrolysis are utilized to reduce viscosity for biodiesel production. However, transesterification is considered one of the best processes for obtaining maximum yield with effective properties compared to diesel properties [6].

In experimental investigations, biodiesel MME and diesel have been used, and the properties of MME and diesel have also been determined. During the combustion of IC engines, heat loss is a major problem affecting engine efficiency, fuel consumption, and emissions. Heat energy loss reduces engine performance and efficiency when thermal energy is rejected to the atmosphere through various modes of heat transfer. Many experimental studies have been conducted to understand heat transfer within the combustion chamber, with factors such as engine load, speed, compression ratio, ignition timing, fuel pressure variation, and equivalence ratio affecting heat transfer.

Applying Thermal Barrier Coating (TBC) to the piston crown and valve transforms a Direct Injection (DI) conventional diesel engine into a Low Heat Rejection (LHR) engine, reducing heat loss [7]. Enhancing the LHR engine with effective TBC promises lower fuel consumption, higher thermal efficiency, lower emissions, and elimination of the cooling system [8]. Various ceramic coatings such as Mullite, AL2O3, TiO2, CaO/MgO–ZrO2, and Yttria-stabilized Zirconia (YSZ) have been used in several engine applications [9]. Thermal barrier coatings like Al2O3, Ca/Mg-PSZ, Mullite, and TiO2 are considered suitable substitutes for YSZ due to their properties for engine applications [10].

LOW HEAT REJECTION ENGINE

Ceramic materials have been utilized in engines for many years, particularly in the context of Low Heat Rejection (LHR) Engines. These materials offer advantages such as lower heat conduction coefficients and reduced weight compared to conventional engine materials. In recent times, ceramic materials have seen significant development in enhancing the performance of diesel engines, as observed in studies by Gatowski et al. [14] and Kamo et al. [15].

Selection of Thermal Barrier Coating (TBC) Materials for IC Engines

Choosing the right TBC material is crucial for ensuring optimal engine performance and durability under demanding conditions within the combustion chamber. The key requirements for high-quality TBC include:

- Chemical inertness
- Strong adherence capability to metallic substrates
- High melting point
- Low thermal conductivity
- No phase change within the room temperature range
- Matching thermal expansion coefficient with the metallic substrate (Kam et al. [15], Abedin et al. [16])

Among various ceramic materials used as TBC in diesel engines, Mullite has shown promising physical properties, including low thermal conductivity, high corrosion resistance, high hardness, and good thermal shock resistance below 1273 K. The physical properties of Mullite as a TBC material are summarized in Table 1 below. These properties make Mullite a suitable candidate for applications in IC engines.

Table 1: Properties of Mullite

Property	**Value**
Melting Point	2123 K
Poisson's Ratio	0.25
Thermal Conductivity (λ)	3.3 W/mK
Young's Modulus	127 GPa
Thermal Expansion Coefficient (α)	5.3x10^-6 (1400 K)
	(293 K - 1273 K)

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By leveraging the properties of Mullite, it is possible to develop effective thermal barrier coatings that enhance engine performance and efficiency in IC engine applications.

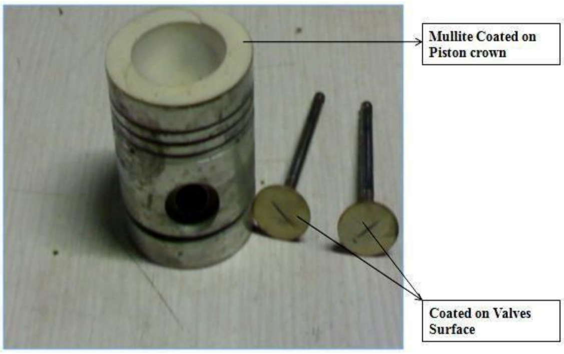

Figure 1: Mullite Coated to Piston Crown and Valves Surface

The research aims to enhance the performance of Low Heat Rejection (LHR) engines using diesel and biodiesel fuels while maintaining a constant fuel injection pressure. To achieve this, a single-cylinder diesel engine was converted into an LHR engine by applying a 0.5mm thick layer of Mullite onto the valves and piston crown, as depicted in Figure 1. The experiment involves analyzing the performance and emission characteristics with standard diesel and biodiesel, both with and without Thermal Barrier Coating (TBC).

TRANSESTERIFICATION PROCESS

In the transesterification process, Neem oil is initially preheated to a temperature between 65ºC to 70ºC for 30 minutes to remove moisture content. Following preheating, 1000ml of Neem oil is mixed with 14 grams of potassium hydroxide and 300ml of methanol. This mixture is heated to 55ºC, and simultaneously stirred for 60 minutes. During this process, the chemicals react with the Neem oil to produce Neem Methyl Ester (MME). Once the reaction is complete, the mixture is allowed to settle in a separating flask for 24 hours. After settling, glycerine separates from the MME, which is then washed with warm distilled water at 45°C to remove residual catalyst or soap content. The washed MME is then heated at 100°C for 30 minutes to remove any remaining water traces. The final product obtained is Neem Biodiesel, ensuring maximum yield, as illustrated in Figure 2 below.

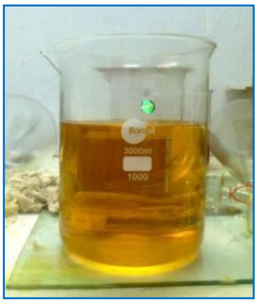

Figure2:Final Product of Pure Neem Biodiesel

4. FUEL PROPERTIES

The table below presents various physical properties of diesel and Neem Methyl Ester (MME) fuels. These properties were tested in the laboratory of MallaReddy Engineering College (A), Secunderabad, Telangana, India. The properties of the MME fuel adhere to the standards of ASTM D 6751 and EN 14214.

Properties	Diesel	MME
Density (15°C), kg/m3	835	872
Specific gravity	0.850	0.916
Kinematic viscosity at 40°C, mm2/s	2.4	4.0
Calorific Value (KJ/kg)	42930	39400
Flash Point (°C)	70	127
Fire Point (°C)	76	136
Cloud Point (°C)	-10 to -15	6
Pour Point (°C)	-35 to -15	1
Colour	Light	Dark yellow brown
Cetane number	51	46
Aniline point (°C)	69	63
Iodine value	NM	60
Diesel index	150	145

Note: NM = Not measured

5. EXPERIMENTAL SETUP

Engine Test: A 3.5 kW single bore diesel engine with a fixed speed of 1500 rpm and water cooling system is utilized for the investigation to enhance engine performance and reduce harmful emissions. The schematic of the experimental setup is depicted in Figure 3. A hydraulic dynamometer is employed for loading the engine.

Table 3: Engine Specifications

Specifications	Values
Name of Engine	Kirloskar
Stroke	4
Type of cooling	Water Cooled
B.H.P.	5
Stroke length	110 mm
Bore	80 mm
No. of Cylinder	1
Compression Ratio	16.5:1
Speed	1500 rpm
Fuel Injection Pressure	200 Bar

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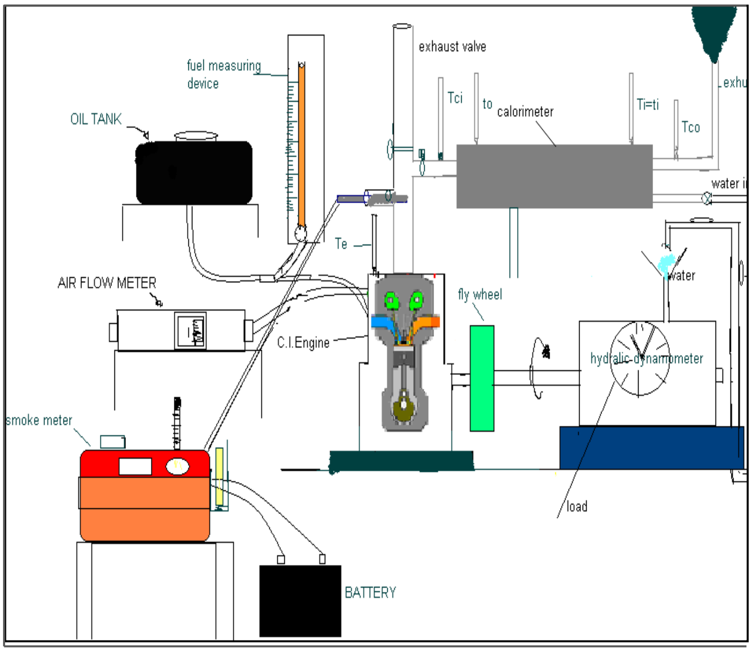

Figure 3: Schematic Plan of Experimental Setup

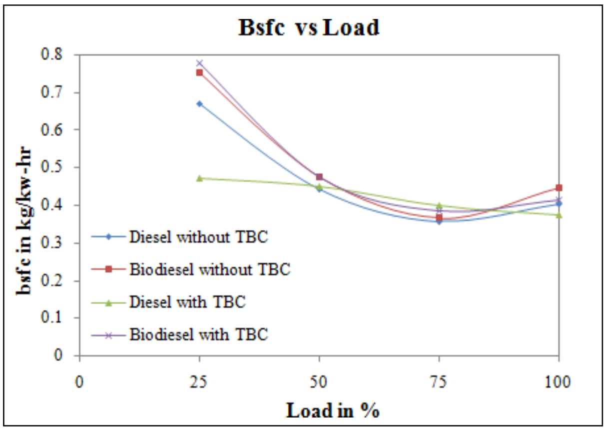

Figure 4: BSFC vs Load

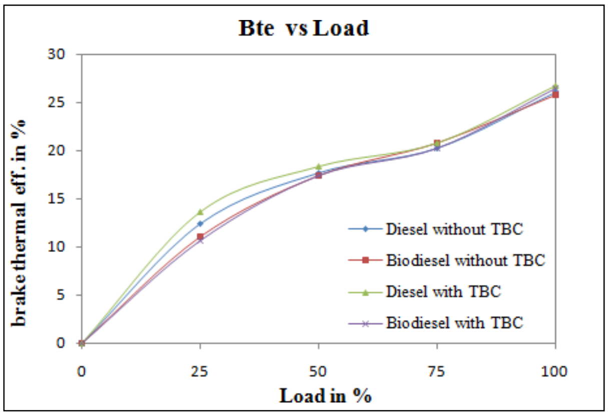

Figure 5: BTE vs Load

6. RESULTS AND DISCUSSIONS

Performance and Emission Parameters

Brake Specific Fuel Consumption (BSFC): Figure 4 illustrates the variation of brake specific fuel consumption (BSFC) with load at 200 bar pressure, with and without Thermal Barrier Coating (TBC) for different fuels. Diesel exhibits lower fuel consumption compared to Neem Methyl Ester (MME) oil. At full load, the BSFC without TBC for diesel is 0.40 kg/kW-hr, whereas for biodiesel, it is 0.44 kg/kW-hr. With TBC, the BSFC at full load for diesel is 0.37 kg/kW-hr, and for biodiesel, it is kg/kW-hr. Notably, at 25% load, diesel with TBC shows lower fuel consumption. The use of TBC increases biodiesel fuel consumption due to its lower calorific value.

Figure 5 depicts the variation of brake thermal efficiency (BTE) with load at 200 bar pressure. The experiment conducted with and without TBC for different fuels is presented. At 25% load condition, diesel with TBC shows improvement. However, at full load condition, there is no significant improvement due to higher viscosity leading to poor atomization, fuel vaporization, and combustion.

Exhaust Gas Temperature: Figure 6 shows the variation of exhaust gas temperature with load at 200 bar injection pressure. The results indicate that, in all cases, the exhaust gas temperature increases with the increase in load. For both diesel and biodiesel without TBC, the MME oil exhibits the highest exhaust gas temperature at 265°C, whereas diesel records 255°C. With TBC, the highest exhaust gas temperature for MME oil is 427°C, compared to diesel at 337°C. MME oil, especially with TBC, shows higher exhaust gas temperature due to its higher combustion temperature and the presence of more oxygen, resulting in a higher peak combustion temperature. Diesel and MME without TBC exhibit lower exhaust gas temperature compared to those with TBC, possibly due to the higher combustion temperature of TBC, which absorbs more heat during the combustion process.

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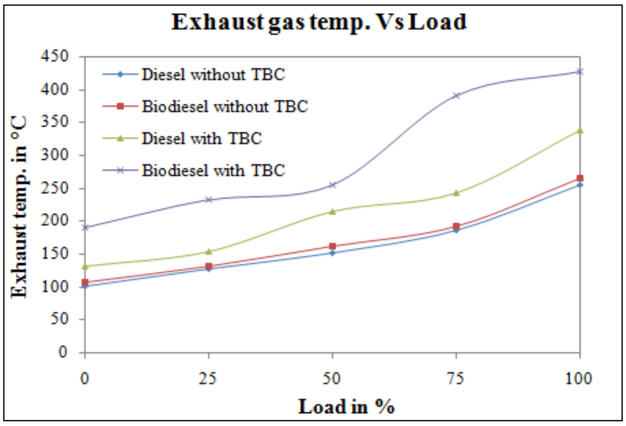

Figure 6: Exhaust Gas Temperature vs Load

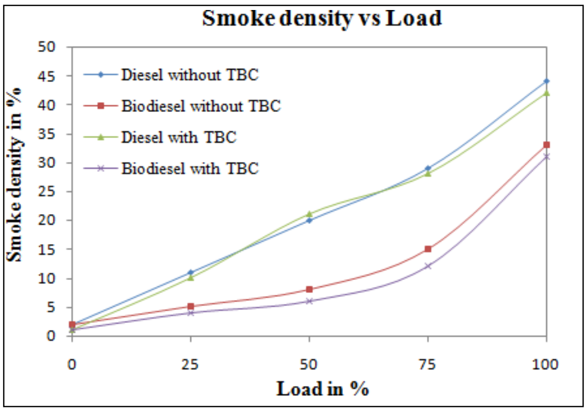

Figure 7: Smoke Density vs Load

The variation of smoke density with load is shown in Figure 7. The smoke density of Neem Methyl Ester (MME) with and without TBC was significantly reduced compared to diesel with and without TBC. This reduction is attributed to biodiesel's better vaporization effect at higher combustion temperatures and the higher oxygen content present in biodiesel.

CO Emissions

Figure 8 illustrates the variation of carbon monoxide (CO) emissions with load at 200 bar injection pressure. The results, compared with and without TBC, fueled with diesel and biodiesel, indicate increased CO emissions at 100% load compared to other loads (0%, 25%, 50%, and 75%). However, at loads ranging from 1% to 75%, CO emissions were lower due to improvements in combustion and the higher oxygen content in biodiesel.

Figure 8: CO Emissions vs Load

HC Emissions

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Figure 9 compares the hydrocarbon (HC) emissions of diesel and biodiesel at 200 bar injection pressure with and without TBC. Biodiesel exhibits significantly lower HC emissions compared to diesel. At maximum load without TBC, HC emissions are 90 (PPM) for diesel and 47 (PPM) for MME. At full load, there is a remarkable reduction in HC emissions, with 63 (PPM) for diesel and 45 (PPM) for biodiesel with TBC. This reduction is attributed to the increase in combustion temperature resulting from decreased heat losses and the higher oxygen content in biodiesel.

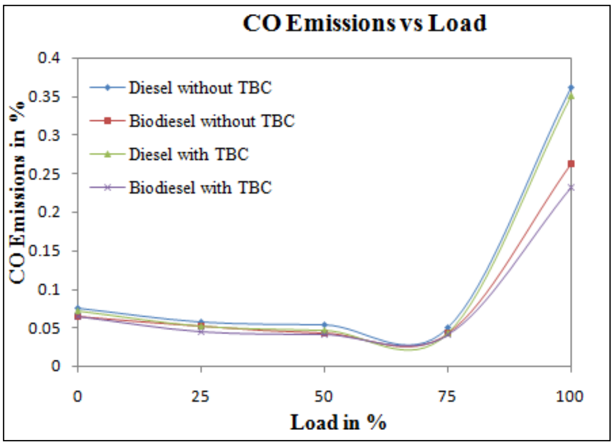

Figure 9: HC Emissions vs Load

NOx Emissions

The variation of Nitrogen Oxide (NOx) emissions with load at 200 bar pressure, with and without TBC for diesel and MME fuels, is presented in Figure 10. NOx is formed by oxidizing nitrogen in the atmosphere at sufficiently high temperatures. Biodiesel, with and without TBC, causes higher NOx emissions due to the higher oxygen levels present, which aids in better combustion and temperature increase. Diesel without TBC exhibits lower NOx emissions.

7. CONCLUSIONS

In conclusion, various technologies with and without TBC have been studied to improve engine performance with Neem biodiesel in Compression Ignition (CI) engines. Experiments were conducted with MME fuel and TBC technologies, maintaining a constant fuel injector pressure of 200 bar and engine speed of 1500 rpm. The important conclusions drawn from the investigation are as follows:

- Neem methyl ester properties comply with ASTM D 6751 and EN 14214 specifications, with properties slightly higher than diesel, except for calorific value.
- The transformation of the diesel engine to an LHR engine with TBC modification showed improvements in performance and emission characteristics.
- Diesel exhibits lower fuel consumption compared to MME biodiesel, with TBC increasing biodiesel consumption due to its lower calorific value.
- Brake thermal efficiency significantly improves at 25% load with diesel and TBC.

- Lower exhaust gas temperatures are achieved with TBC using both MME and diesel, attributed to increased heat retention during combustion.
- Smoke density is significantly reduced with MME, with or without TBC, due to the higher oxygen content.
- CO emissions decrease moderately with MME biodiesel, particularly with TBC, attributed to the presence of oxygen molecules.
- HC emissions are remarkably reduced with MME biodiesel, especially with TBC, due to increased combustion temperature and oxygen content.
- Biodiesel, with or without TBC, results in higher NOx emissions compared to diesel, due to better combustion facilitated by higher oxygen levels.

Hence, Neem biodiesel shows promise as an alternative fuel for diesel engines, especially with TBC modifications.

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