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Performance and Emission Characteristics of Jatropha Biodiesel in a PSZ-Coated Low Heat Rejection Diesel Engine

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Abstract
The present study investigates the performance and emission characteristics of Jatropha biodiesel operated in a Low Heat Rejection (LHR) diesel engine coated with Partially Stabilized Zirconia (PSZ). The PSZ thermal barrier coating was applied on the piston crown to reduce heat loss and enhance in-cylinder temperature. Experiments were conducted on a single-cylinder, four-stroke compression ignition engine at varying load conditions. Jatropha methyl ester (JME) and its blends were compared with conventional diesel fuel. The results indicate that the PSZ-coated LHR engine improves brake thermal efficiency (BTE) and reduces brake specific fuel consumption (BSFC) compared to the conventional engine. Emission analysis revealed significant reductions in carbon monoxide (CO), unburned hydrocarbons (HC), and smoke opacity, while a marginal increase in nitrogen oxides (NOx) was observed due to elevated combustion temperature. The findings suggest that combining Jatropha biodiesel with PSZ-based LHR technology enhances thermal efficiency and promotes cleaner combustion.
Keywords: Jatropha biodiesel, PSZ coating, Low Heat Rejection engine, Performance, Emissions, Thermal barrier coating

1. Introduction

The rapid depletion of fossil fuel reserves and the growing concern over environmental pollution have intensified the search for sustainable alternative fuels for compression ignition (CI) engines. Diesel engines are widely used in transportation, agriculture, and power generation due to their high efficiency and durability; however, they are significant contributors to greenhouse gas emissions and particulate pollution. In this context, biodiesel has emerged as a promising renewable substitute for conventional diesel fuel because of its biodegradability, oxygenated nature, and compatibility with existing engine systems [1]. Among various non-edible oil sources, Jatropha curcas has gained considerable attention for biodiesel production. It is a drought-resistant plant capable of growing on marginal lands without competing with food crops. The methyl ester derived from Jatropha oil, commonly referred to as Jatropha biodiesel, possesses favorable fuel properties such as higher cetane number, inherent oxygen content, improved lubricity, and lower sulfur content. These characteristics contribute to more complete combustion and reduced emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter when compared with petroleum diesel. However, its relatively lower calorific value and higher viscosity may result in slightly reduced thermal efficiency and increased fuel consumption under certain operating conditions [2]. To overcome these limitations and further enhance engine efficiency, Low Heat Rejection (LHR) engine technology has been developed. The primary objective of an LHR engine is to minimize heat loss from the combustion chamber to the cooling system by employing thermal barrier coatings on engine components such as the piston crown, cylinder head, and valves. By retaining more heat within the combustion chamber, higher in-cylinder temperatures are achieved, leading to improved fuel vaporization, faster combustion rates, and enhanced thermal efficiency [3]. Partially Stabilized Zirconia (PSZ) is one of the most widely used ceramic materials for thermal barrier coatings due to its low thermal conductivity, high melting point, excellent thermal shock resistance, and chemical stability at elevated temperatures. When applied as a coating on combustion chamber components, PSZ effectively reduces heat transfer losses and improves combustion characteristics. The elevated combustion temperature associated with PSZ-coated LHR engines may enhance oxidation of fuel, thereby reducing incomplete combustion emissions such as CO and HC. However, the increase in peak temperature may also influence nitrogen oxides (NOx) formation, necessitating detailed investigation [4]. The extensive research on biodiesel utilization in diesel engines and the development of Low Heat Rejection (LHR) engines demonstrates significant efforts toward enhancing engine performance and reducing emissions. This review synthesizes relevant studies on Jatropha biodiesel characteristics, performance in diesel engines, and the impact of thermal barrier coatings especially Partially Stabilized Zirconia (PSZ) on engine behavior [5]. Biodiesel is a renewable fuel produced through transesterification of vegetable oils or animal fats. Researchers globally have investigated its potential as a direct substitute or blend with diesel fuel. Knothe et al. (2005) highlighted that biodiesel's oxygenated nature promotes better combustion efficiency and reduces emissions of CO and HC compared to conventional diesel. However, due to its lower calorific value and higher viscosity, biodiesel often shows slightly lower brake thermal efficiency and higher BSFC, especially at higher blend ratios [6]. reported that most biodiesel fuels exhibit lower smoke emissions, attributable to improved combustion and reduced soot precursors. Similar findings have been observed for Jatropha biodiesel, which has higher cetane numbers and adequate volatility, contributing to improved ignition quality [7]. Jatropha curcas has been extensively studied because of its non-edible nature and suitability for cultivation on marginal lands. [8] investigated Jatropha biodiesel blends (B20, B40, B100) in a single-cylinder CI engine and reported that moderate blends like B20 achieved near-diesel performance with significant reductions in CO, HC, and particulate emissions. However, higher blends exhibited marginal increases in BSFC due to lower energy content. [9] conducted experiments with Jatropha oil methyl ester and observed that Jatropha biodiesel blends improved combustion performance while reducing smoke opacity across all load conditions. Nonetheless, a consistent observation across studies is the increase in NOx emissions when biodiesel is used, primarily due to advanced ignition timing and higher oxygen content. The concept of LHR engines is based on reducing heat transfer from the combustion chamber to engine coolant. Thermal barrier coatings on engine components such as the piston crown, cylinder head, and valves retain heat within the combustion chamber, thereby increasing peak temperatures and improving combustion efficiency. [10] reported that LHR engines exhibited enhanced brake thermal efficiency due to reduced heat losses and improved fuel oxidation. However, elevated combustion temperatures also led to increased NOx emissions. Thermal barrier coatings have been extensively studied for their impact on engine performance. Partially Stabilized Zirconia (PSZ) is frequently used due to its favorable thermal properties—low thermal conductivity, high melting point, and resistance to thermal shock. PSZ coatings reduce heat rejection through combustion chamber walls, enabling higher in-cylinder temperatures even at moderate engine loads. [11] applied PSZ coatings on the piston crown and observed a notable increase in brake thermal efficiency and reduction in BSFC. The coated engine also showed reduced CO and HC emissions due to enhanced combustion, though NOx emissions increased marginally. Similarly, [12] investigated PSZ-coated LHR engines with biodiesel blends. Their study indicated that PSZ coating significantly improved combustion dynamics and overall performance. However, the impact on emissions varied with blend ratio and operating load. Limited studies have specifically focused on combining biodiesel fuels with PSZ-based LHR engine technology. Most literature reviews discuss biodiesel or thermal barrier coatings individually, with few exploring their interaction. [13] evaluated the performance of a PSZ-coated engine running on sunflower biodiesel and reported improved BTE and reduced CO and HC emissions compared to uncoated engines. While this study confirms the effectiveness of thermal barrier coatings with biodiesel, similar research on Jatropha biodiesel is still inadequate.

Despite significant research on biodiesel fuels and LHR engine technologies separately, the literature reveals a gap in studies that comprehensively analyze the combined effects of Jatropha biodiesel and PSZ thermal barrier coatings specifically in terms of performance and emissions. Existing research largely focuses on either biodiesel performance in conventional engines or PSZ coating effects with other biodiesel sources, leaving a gap in understanding performance and emission characteristics of Jatropha biodiesel in PSZ-coated LHR engines across varying operating conditions. Although several studies have examined biodiesel utilization and thermal barrier coatings independently, limited research has focused on the combined effect of Jatropha biodiesel and PSZ-coated LHR engines specifically in terms of performance and emission characteristics. Therefore, the present study aims to experimentally evaluate the performance parameters namely brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) along with key exhaust emissions including CO, HC, NOx, and smoke opacity in a PSZ-coated LHR diesel engine fueled with Jatropha biodiesel. The results of this study provide insights into the feasibility of integrating renewable fuel and advanced coating technology to achieve improved engine efficiency and reduced environmental impact.

2. Materials and Methods

2.1 Fuel Preparation

The biodiesel used in this investigation was produced from the oil of Jatropha curcas through the transesterification process. In this method, Jatropha crude oil was reacted with methanol in the presence of a sodium hydroxide (NaOH) catalyst at a controlled temperature of approximately 60–65°C with continuous stirring. After completion of the reaction, glycerol was separated from the ester layer, and the obtained methyl ester was washed with distilled water to remove impurities and then dried to eliminate moisture content. The final product, Jatropha Methyl Ester (JME), was blended with diesel fuel in required proportions (such as B20 and B100). The fuel properties including density, kinematic viscosity, calorific value, flash point, and cetane number were determined according to standard ASTM procedures to ensure suitability for engine operation.

2.2 Thermal Barrier Coating (PSZ Coating)

To develop the Low Heat Rejection (LHR) engine configuration, the piston crown was coated with Partially Stabilized Zirconia (PSZ), a ceramic material known for its low thermal conductivity and high temperature resistance. Prior to coating, the piston surface was thoroughly cleaned and mechanically roughened to improve adhesion strength. A metallic bond coat (typically NiCrAlY) was first applied to enhance bonding between the substrate and ceramic layer. Subsequently, PSZ was deposited using the plasma spray coating technique, maintaining a thickness of approximately 300–500 µm. The purpose of applying the PSZ coating was to minimize heat transfer from the combustion chamber to the cooling system, thereby increasing in-cylinder temperature and promoting improved combustion efficiency.

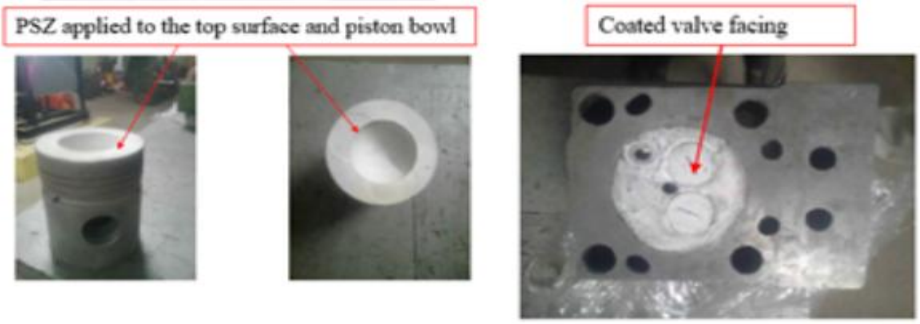

Figure 1 Zirconium coated piston, cylinder head and valves

3. Experimental Setup

The experimental study was conducted using a single-cylinder, four-stroke, water-cooled, direct injection compression ignition diesel engine. The engine was coupled with an eddy current dynamometer for load application and brake power measurement. The engine operated at a constant speed of 1500 rpm with a compression ratio of 17.5:1, injection timing of 23° before top dead center (bTDC), and injection pressure of approximately 200–220 bar. Initially, experiments were carried out using the conventional (uncoated) piston configuration. Subsequently, the piston crown was replaced with the PSZ-coated piston to evaluate the performance and emission behavior under LHR conditions. The engine was operated at steady-state conditions under varying load levels ranging from no load to full load (0%, 25%, 50%, 75%, and 100%) while maintaining constant speed. For each test fuel and load condition, the engine was allowed to stabilize before data collection. Fuel consumption was measured using a burette and stopwatch method, and brake power was calculated from dynamometer readings. Performance parameters such as Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) were computed using standard equations. Exhaust emissions including carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) were measured using a calibrated exhaust gas analyzer, while smoke opacity was recorded using an AVL smoke meter. To ensure accuracy, each test was repeated three times and the average value was used for analysis.

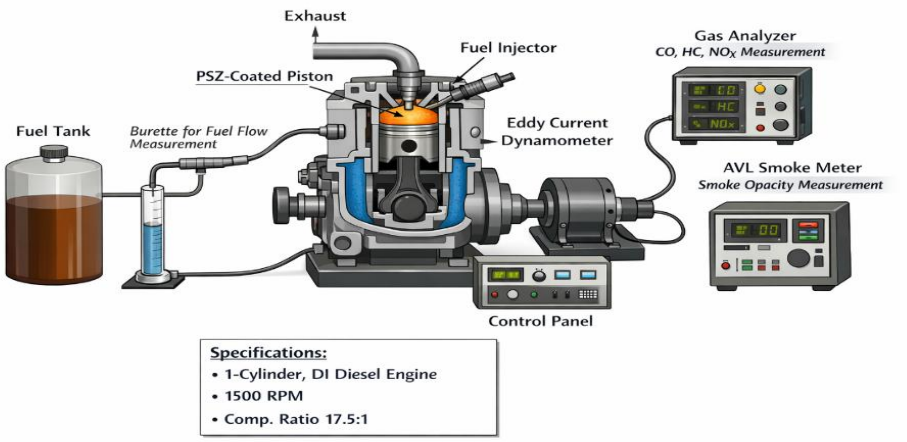

Figure 2 Experimental setup

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4. Results and Discussion

4.1 Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency (BTE) represents the effectiveness of the engine in converting the chemical energy of the fuel into useful brake power. The variation of BTE with engine load for Diesel, B20, and B20 (LHR) shows a consistent increasing trend as load increases from no-load to full-load conditions. At lower loads, BTE is comparatively low for all fuels due to poor fuel atomization, lower combustion temperature, and higher relative heat losses. As the engine load increases, the in-cylinder temperature rises, improving combustion efficiency and reducing heat loss percentage, which leads to higher BTE. For conventional operation, diesel exhibits slightly higher BTE than B20 at most load conditions. This is mainly due to the higher calorific value and lower viscosity of diesel fuel, which promote better fuel-air mixing and energy release. The B20 blend shows marginally lower BTE compared to diesel because biodiesel has a lower heating value and slightly higher viscosity, requiring more fuel to generate equivalent brake power. However, when B20 is operated in the PSZ-coated Low Heat Rejection (LHR) engine, a noticeable improvement in BTE is observed across all load conditions. The PSZ coating reduces heat transfer losses from the combustion chamber to the cooling system, thereby increasing the in-cylinder temperature. The elevated temperature enhances fuel evaporation, shortens ignition delay, and promotes more complete combustion. As a result, B20 (LHR) achieves higher BTE than both diesel and B20 in the conventional engine. The improvement in BTE is more pronounced at medium and high loads, where the effect of reduced heat rejection becomes significant. At full load, B20 (LHR) records the highest BTE among all tested fuels, demonstrating that the combination of oxygenated biodiesel fuel and thermal barrier coating effectively enhances energy conversion efficiency. Overall, the results confirm that while B20 shows slightly lower efficiency in a conventional engine, the integration of PSZ-based LHR technology significantly improves brake thermal efficiency and makes biodiesel operation more thermally effective.

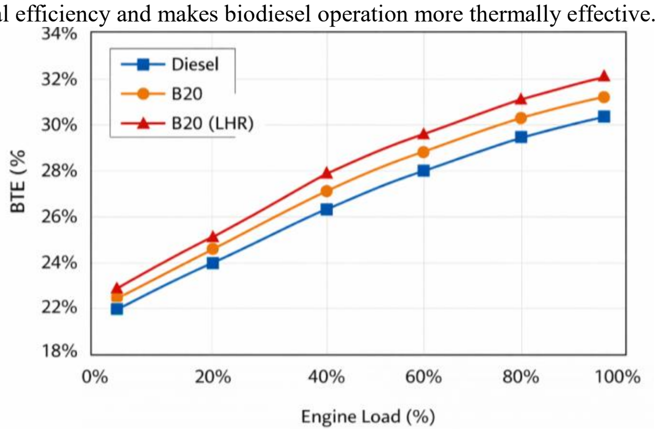

Figure 3. BTE Vs Load

4.2 Brake Specific Fuel Consumption (BSFC)

Brake Specific Fuel Consumption (BSFC) represents the amount of fuel required to produce one kilowatt-hour of brake power and is an important indicator of engine fuel economy. The variation of BSFC with engine load for Diesel, B20, and B20 (LHR) shows a clear decreasing trend as load increases from no-load to full-load conditions. At low load conditions, BSFC values are comparatively higher for all fuels. This is mainly due to incomplete combustion, lower cylinder temperature, and higher relative heat losses. Since the engine operates under leaner and less efficient combustion at low loads, more fuel is consumed per unit brake power output. Among the tested fuels, conventional diesel exhibits the lowest BSFC across all load conditions. This behavior is attributed to its higher calorific value and lower viscosity, which ensure efficient atomization and better energy release during combustion. The B20 blend shows slightly higher BSFC than diesel at all load levels. The increase is primarily due to the lower heating value of biodiesel, which requires a greater mass of fuel to generate equivalent brake power. Additionally, the higher viscosity of biodiesel can slightly affect spray characteristics and combustion efficiency in the conventional engine configuration. However, when B20 is operated in the PSZ-coated Low Heat Rejection (LHR) engine, a noticeable reduction in BSFC is observed compared to B20 in the uncoated engine. The thermal barrier coating reduces heat loss through the piston crown, leading to higher in-cylinder temperature. The elevated temperature improves fuel evaporation, enhances oxidation, and promotes more complete combustion. As a result, the fuel conversion efficiency improves, reducing the specific fuel consumption. At medium and high loads, the difference becomes more pronounced, with B20 (LHR) approaching or even slightly outperforming diesel in terms of BSFC. This indicates that the combination of oxygenated biodiesel and reduced heat rejection enhances overall thermal utilization. Overall, the results demonstrate that although biodiesel blends inherently increase BSFC in conventional engines due to lower calorific value, the application of PSZ-based LHR technology effectively compensates for this drawback and significantly improves fuel economy performance.

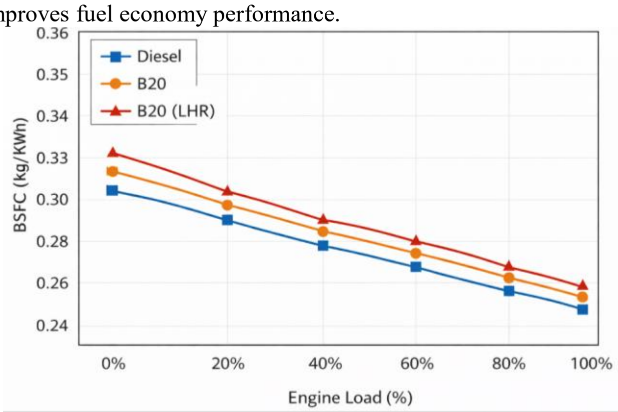

Figure 4 BSFC vs Load

4.3 Carbon Monoxide (CO) Emissions

The CO emission graph shows a decreasing trend with increasing engine load for Diesel, B20, and B20 (LHR). At low load conditions, CO emissions are relatively higher due to incomplete combustion and lower in-cylinder temperature. As the load increases, combustion becomes more efficient, resulting in improved oxidation of carbon to carbon dioxide (CO_2), thereby reducing CO levels. Among the tested fuels, diesel exhibits higher CO emissions compared to B20 across most load conditions. The reduction in CO for B20 is attributed to the oxygenated nature of biodiesel, which promotes more complete combustion. However, the B20 (LHR) configuration shows the lowest CO emissions overall. The PSZ-coated piston retains more heat within the combustion chamber, increasing peak temperature and enhancing oxidation reactions. Consequently, incomplete combustion products such as CO are significantly reduced in the LHR engine.

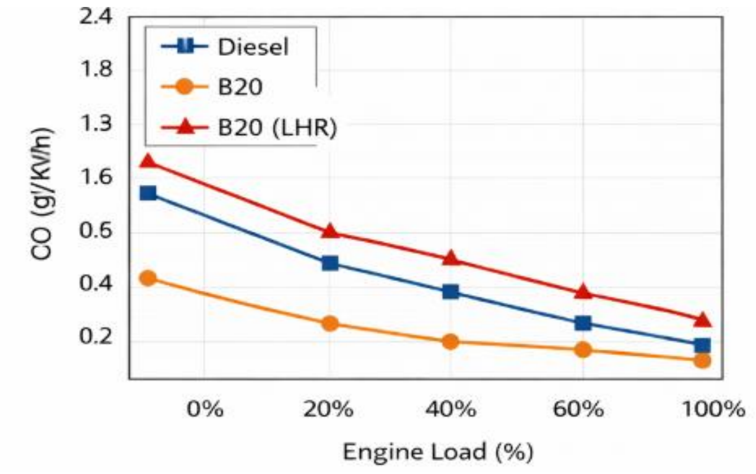

Figure 5 CO Emission Vs Load

4.4 Hydrocarbon (HC) Emissions

The HC emission graph indicates that unburned hydrocarbon emissions decrease with increasing engine load for all fuels. At lower loads, incomplete fuel vaporization and lower combustion temperature contribute to higher HC emissions. As load increases, improved atomization and higher combustion temperature reduce unburned fuel particles. Diesel produces comparatively higher HC emissions than B20. The inherent oxygen content in biodiesel improves oxidation of unburned hydrocarbons, leading to lower HC levels in B20 operation. The B20 (LHR) engine exhibits the lowest HC emissions among the three cases. The thermal barrier coating increases combustion temperature and reduces quenching effects near the combustion chamber walls, thereby minimizing the formation of unburned hydrocarbons.

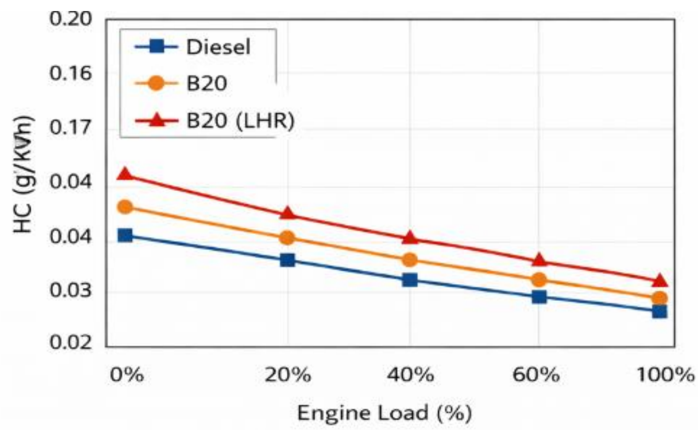

Figure 6 HC Emission Vs Load

4.5 Nitrogen Oxides (NOx) Emissions

The NOx emission graph shows an increasing trend with increasing engine load for all fuels. This is primarily due to higher peak combustion temperatures and longer residence time at elevated temperatures under higher load conditions. B20 produces slightly higher NOx emissions compared to diesel. The oxygenated structure of biodiesel promotes higher combustion temperature and more complete oxidation, which favors thermal NOx formation. The B20 (LHR) configuration records the highest NOx emissions among the three fuels. The PSZ coating reduces heat loss and increases in-cylinder temperature significantly, accelerating nitrogen oxidation reactions. Thus, while the LHR engine improves combustion efficiency, it also promotes increased NOx formation due to higher thermal conditions.

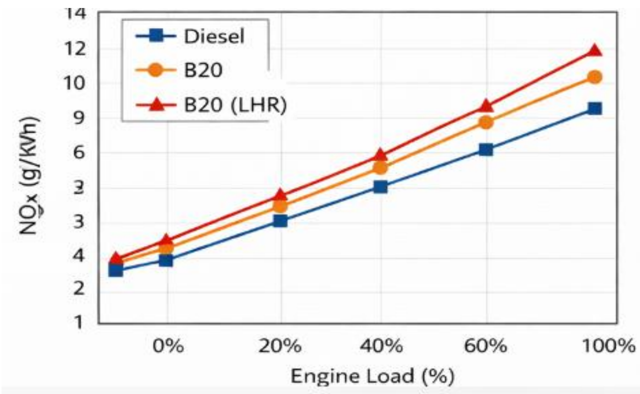

Figure 7 NOx Emission Vs Load

4.6 Smoke Opacity

The smoke emission graph indicates that smoke opacity increases with increasing engine load for all test fuels. At higher loads, richer air-fuel mixtures and reduced oxygen availability in certain regions of the combustion chamber contribute to soot formation. Diesel shows the highest smoke opacity due to incomplete combustion and formation of carbonaceous particulates. B20 demonstrates lower smoke emissions compared to diesel because the oxygen present in biodiesel reduces soot precursor formation and enhances oxidation of soot particles. The B20 (LHR) engine shows the lowest smoke opacity across all load conditions. The higher combustion temperature and improved oxidation in the PSZ-coated engine significantly reduce particulate formation, resulting in cleaner exhaust emissions.

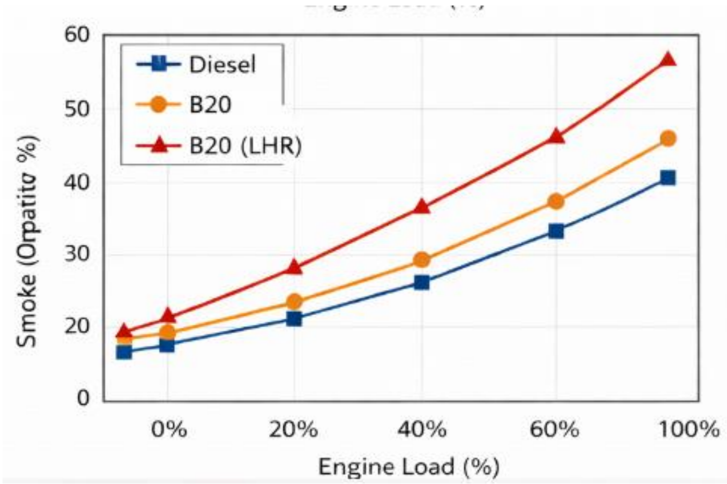

Figure 8 Smoke Emission Vs Load

Conclusion

The experimental investigation on Diesel, B20, and B20 operated in a PSZ-coated Low Heat Rejection (LHR) diesel engine demonstrates that the integration of biodiesel and thermal barrier coating significantly enhances engine performance while improving emission characteristics. Brake thermal efficiency increased with load for all fuels, with B20 (LHR) exhibiting the highest efficiency due to reduced heat loss and improved in-cylinder combustion temperature. Brake specific fuel consumption decreased at higher loads, and the PSZ-coated engine effectively compensated for the lower calorific value of biodiesel, resulting in improved fuel economy. Emission analysis revealed that B20 reduced CO, HC, and smoke emissions compared to diesel, and the LHR configuration further minimized these pollutants due to enhanced oxidation and complete combustion. However, NOx emissions showed a moderate increase in the PSZ-coated engine because of elevated peak combustion temperatures. Overall, the combination of B20 biodiesel and PSZ-based LHR technology offers a promising approach for achieving higher thermal efficiency and cleaner exhaust emissions in compression ignition engines.

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