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Experimental Investigation of ZnO Nanoparticle-Blended Biodiesel on Engine Emissions

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Abstract
The depletion of fossil fuels and the stringent emission norms have accelerated the search for cleaner alternative fuels in compression ignition (CI) engines. Biodiesel has emerged as a promising renewable substitute; however, its higher viscosity and oxygen content often influence combustion and emission characteristics. In this study, zinc oxide (ZnO) nanoparticles were dispersed into biodiesel–diesel blends to enhance combustion efficiency and reduce exhaust emissions. ZnO nanoparticles were added in varying concentrations (25, 50, and 75 ppm) using an ultrasonication process to ensure uniform dispersion. The experimental investigation was conducted on a single-cylinder, four-stroke, direct injection diesel engine under different load conditions. The results revealed that ZnO nanoparticle addition improved brake thermal efficiency (BTE) and significantly reduced carbon monoxide (CO), hydrocarbon (HC), and smoke emissions compared to neat biodiesel. A slight increase in NOx emissions was observed at higher nanoparticle concentrations due to improved combustion temperature. Overall, ZnO nanoparticle-blended biodiesel demonstrated superior emission characteristics and combustion performance compared to conventional biodiesel blends.

Keywords: Biodiesel, Zinc Oxide Nanoparticles, CI Engine, Emission Analysis, Combustion Characteristics, Nano-Additives.

1. Introduction

The rapid depletion of fossil fuel reserves and the continuous rise in environmental pollution have intensified the search for sustainable and cleaner alternative fuels for compression ignition (CI) engines. Diesel engines are extensively used in transportation, agriculture, and power generation sectors due to their high thermal efficiency and durability. However, they are significant contributors to harmful emissions such as carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM), which adversely affect air quality and human health. Stringent emission regulations worldwide have therefore necessitated the development of eco-friendly fuel alternatives [1]. Biodiesel has emerged as one of the most promising renewable substitutes for conventional diesel fuel. It is produced through the transesterification of vegetable oils, non-edible oils, waste cooking oils, or animal fats with alcohol in the presence of a catalyst. Biodiesel offers several advantages, including biodegradability, oxygenated nature, higher cetane number, and near carbon-neutral lifecycle characteristics. Moreover, it can be used in existing diesel engines with little or no modification. However, despite these advantages, biodiesel exhibits certain limitations such as higher viscosity, lower calorific value, poor atomization characteristics, and relatively higher NOx emissions compared to mineral diesel. These drawbacks can affect combustion quality and engine performance [2]. To overcome these limitations, recent research has focused on the use of nano-additives in biodiesel blends. Nanoparticles possess a very high surface area-to-volume ratio, enhanced catalytic activity, and superior thermal conductivity. When dispersed in fuel, they can improve atomization, shorten ignition delay, and enhance heat transfer within the combustion chamber. Metal oxide nanoparticles such as cerium oxide (CeO_2), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and zinc oxide (ZnO) have been widely investigated for their ability to improve combustion efficiency and reduce emissions [3]. Among these, zinc oxide (ZnO) nanoparticles have attracted considerable attention due to their strong oxidation potential, oxygen buffering capacity, and thermal stability. ZnO nanoparticles can promote complete combustion by supplying additional oxygen at the reaction zone, thereby reducing incomplete combustion products such as CO and HC. Furthermore, their catalytic nature enhances the oxidation of soot particles, leading to a reduction in smoke emissions. The improved combustion process can also influence in-cylinder temperature and heat release characteristics, which may affect NOx formation [4]. Although several studies have reported the positive influence of metal oxide nanoparticles on biodiesel combustion, limited experimental data are available on the optimal concentration of ZnO nanoparticles and their specific impact on emission characteristics under varying engine load conditions. Therefore, the present study aims to experimentally investigate the effect of ZnO nanoparticle-blended biodiesel on engine emissions in a single-cylinder direct injection diesel engine. The study evaluates key emission parameters such as CO, HC, NOx, and smoke opacity at different load conditions and compares the results with conventional biodiesel blends [5]. Biodiesel has been extensively investigated as a renewable and sustainable alternative to conventional diesel fuel for compression ignition (CI) engines. Due to its inherent oxygen content, higher cetane number, and biodegradable nature, biodiesel has demonstrated significant reductions in carbon monoxide (CO), unburned hydrocarbons (HC), and particulate emissions compared to mineral diesel. However, several studies have reported certain limitations such as higher viscosity, lower calorific value, poor atomization characteristics, and a tendency to produce slightly higher nitrogen oxides (NOx) emissions. These drawbacks can negatively affect combustion efficiency and overall engine performance, especially at higher blend ratios and load conditions [6]. To overcome these limitations, researchers have explored the incorporation of nano-additives into biodiesel blends. Nanoparticles possess unique physicochemical properties such as high surface area-to-volume ratio, enhanced catalytic reactivity, improved thermal conductivity, and oxygen buffering capability. These characteristics enable nanoparticles to accelerate combustion reactions, promote better fuel–air mixing, shorten ignition delay, and enhance heat transfer within the combustion chamber. Consequently, the addition of nanoparticles has been reported to improve brake thermal efficiency (BTE) and reduce incomplete combustion products [7]. Among various nano-additives, metal oxide nanoparticles such as cerium oxide (CeO_2), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and zinc oxide (ZnO) have received considerable attention. Cerium oxide is known for its oxygen storage and release mechanism, which enhances soot oxidation and reduces smoke emissions. Aluminum oxide and titanium dioxide nanoparticles improve combustion stability and heat transfer characteristics, contributing to lower HC and CO emissions. However, the effectiveness of these nanoparticles strongly depends on their concentration, dispersion stability, and interaction with the base fuel [8]. Zinc oxide (ZnO) nanoparticles have recently emerged as a promising additive due to their strong oxidation potential, thermal stability, and catalytic properties. Previous experimental investigations indicate that ZnO nanoparticles enhance combustion efficiency by supplying additional oxygen at the reaction zone and facilitating complete oxidation of fuel molecules. This leads to significant reductions in CO, HC, and smoke emissions. Nevertheless, some studies have observed a marginal increase in NOx emissions due to elevated in-cylinder temperatures resulting from improved combustion. Therefore, optimizing nanoparticle concentration is critical to achieving a balance between emission reduction and performance enhancement [9]. Although several researchers have demonstrated the benefits of nano-additized biodiesel, limited systematic studies focus specifically on the emission characteristics of ZnO nanoparticle-blended biodiesel under varying engine load conditions. Hence, further experimental investigation is necessary to establish the emission behavior, identify optimal dosage levels, and evaluate the feasibility of ZnO nanoparticles as effective combustion catalysts in CI engines.

This investigation seeks to provide a comprehensive understanding of the emission behavior of nano-enhanced biodiesel and to determine the feasibility of ZnO nanoparticles as effective combustion catalysts for sustainable diesel engine operation.

2. Materials and Methods

2.1 Biodiesel Preparation

Biodiesel used in this study was produced through the transesterification process of vegetable oil using methanol in the presence of a homogeneous alkaline catalyst (NaOH). The oil was initially preheated to remove moisture and impurities. The methanol–catalyst mixture was then added to the heated oil and stirred continuously at a controlled temperature of 55–60°C for approximately 60–90 minutes. After completion of the reaction, the mixture was allowed to settle in a separating funnel for 24 hours to facilitate the separation of glycerol from biodiesel. The obtained biodiesel was washed with warm distilled water to remove residual catalyst and impurities and then dried to eliminate moisture. The final product was filtered and stored in airtight containers for further blending.

2.2 Preparation of ZnO Nanoparticle-Blended Fuel

Zinc oxide (ZnO) nanoparticles with an average particle size of 20–50 nm and purity greater than 99% were used as fuel additives. The required quantity of nanoparticles (25 ppm, 50 ppm, and 75 ppm by weight) was measured using a precision digital weighing balance. The nanoparticles were initially mixed with biodiesel using magnetic stirring for 30 minutes to ensure preliminary dispersion. Subsequently, ultrasonication was performed for 45 minutes to achieve uniform and stable dispersion and to minimize agglomeration. A small quantity of surfactant was added to enhance stability and prevent sedimentation. The prepared nano-fuel blends were visually inspected and tested for short-term stability before conducting engine experiments.

2.3 Scanning Electron Microscopy (SEM) Analysis of ZnO Nanoparticles

Scanning Electron Microscopy (SEM) analysis was carried out to examine the surface morphology and particle size distribution of the zinc oxide (ZnO) nanoparticles used in the present investigation. SEM provides detailed information regarding the external structure, shape, and dispersion characteristics of nanoparticles, which are crucial in determining their catalytic behavior during combustion. The SEM micrographs revealed that the ZnO nanoparticles predominantly exhibit spherical to quasi-spherical morphology. A slight degree of agglomeration was observed, which is commonly associated with nanoparticles due to their high surface energy and strong inter-particle attractive forces. Despite minor clustering, the particles appeared relatively uniform and well distributed, indicating effective synthesis and proper handling before blending with biodiesel. The average particle size observed from SEM analysis was found to be in the range of 20–50 nm, confirming the nanoscale dimension of the material. The small particle size ensures a high surface area-to-volume ratio, which enhances catalytic activity and promotes efficient oxidation reactions during combustion. This characteristic is particularly beneficial in reducing incomplete combustion products such as carbon monoxide and hydrocarbons. Overall, the SEM analysis confirms that the morphological characteristics of ZnO nanoparticles are suitable for their application as nano-additives in biodiesel blends. The fine particle structure and high surface reactivity contribute significantly to improved combustion efficiency and emission reduction in compression ignition engines (Figure 1).

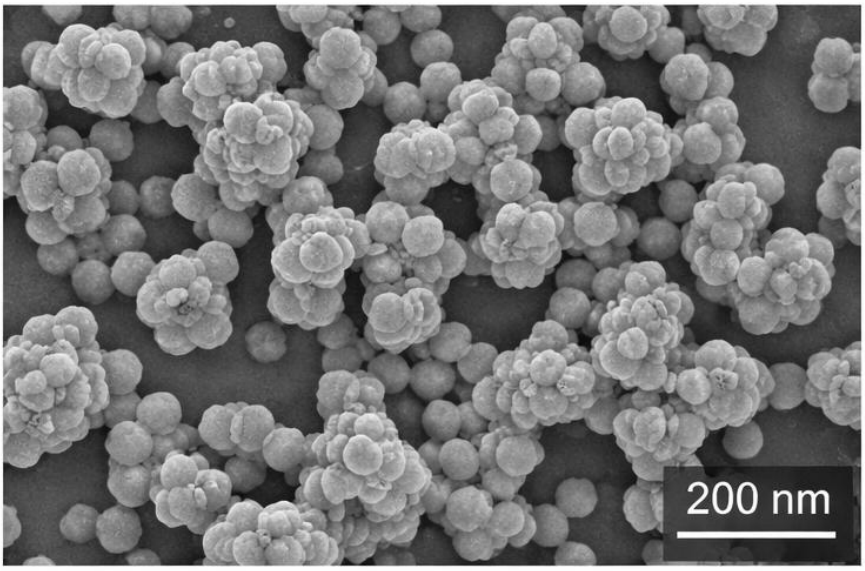

Figure 1 SME Analysis of ZnO Nanoparticles

3. Experimental Setup

The experimental investigation was carried out on a laboratory-scale compression ignition (CI) engine test rig to evaluate the performance and emission characteristics of ZnO nanoparticle-blended biodiesel. A single-cylinder, four-stroke, water-cooled, direct injection (DI) diesel engine was used for the experiments. The engine was coupled with an eddy current dynamometer to apply and control the load during testing. The engine speed was maintained constant at 1500 rpm throughout the experimentation. The engine specifications are summarized as follows: single-cylinder, four-stroke, direct injection type; rated power of approximately 3.5–5.2 kW; water cooling system; and standard compression ratio as per manufacturer settings. Fuel consumption was measured using a burette and stopwatch arrangement, while brake power was calculated from dynamometer readings. An exhaust gas analyzer was employed to measure key emission parameters such as carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx). Smoke opacity was measured using a standard smoke meter connected to the exhaust outlet. Exhaust gas temperature was recorded using a thermocouple positioned in the exhaust manifold. Before conducting the experiments, the engine was allowed to run with neat diesel until steady-state operating conditions were achieved. Subsequently, biodiesel and ZnO nanoparticle-blended biodiesel samples were tested at different load conditions (0%, 25%, 50%, 75%, and 100% load). At each load, readings were recorded after stabilization to ensure accuracy and repeatability. All experiments were repeated to minimize experimental uncertainty and improve data reliability. The overall experimental setup enabled systematic evaluation of combustion behavior and emission characteristics under controlled and consistent operating conditions.

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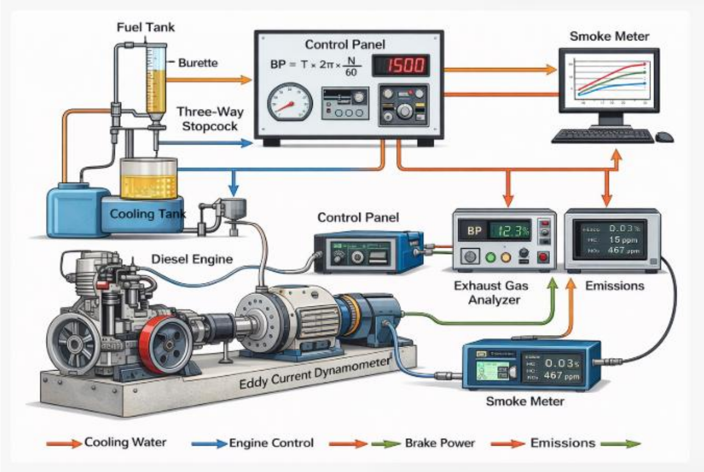

Figure 2 Experimental Setup

4.Results and Discussion

4.1 Brake Thermal Efficiency (BTE)

The variation of brake thermal efficiency (BTE) with engine load for Diesel, B20, B20 + ZnO (50 ppm), and B20 + ZnO (100 ppm) demonstrates a clear influence of nanoparticle addition on engine performance. BTE increased progressively with load for all tested fuels due to improved combustion temperature and enhanced fuel–air interaction at higher loads. At lower loads (0–25%), all blends exhibited relatively lower efficiency because of incomplete combustion and lower in-cylinder temperature. Diesel showed slightly higher BTE than neat B20 owing to its higher calorific value and better volatility. However, the incorporation of ZnO nanoparticles significantly improved the efficiency of the B20 blend. The B20 + ZnO (50 ppm) blend exhibited the highest BTE across medium and full load conditions, indicating enhanced combustion efficiency. This improvement can be attributed to the catalytic activity of ZnO nanoparticles, which promote better oxidation of fuel molecules, shorten ignition delay, and enhance heat release rate. The oxygen buffering capability and high surface area of ZnO nanoparticles facilitate more complete combustion, resulting in better conversion of chemical energy into mechanical power. Although the B20 + ZnO (100 ppm) blend also showed improved BTE compared to neat B20, its efficiency was slightly lower than the 50 ppm blend at higher loads. This may be due to increased nanoparticle concentration leading to minor agglomeration or marginal changes in fuel properties, slightly affecting combustion characteristics. Overall, the results indicate that the addition of ZnO nanoparticles enhances brake thermal efficiency, with 50 ppm identified as the optimum concentration among the tested blends [10].

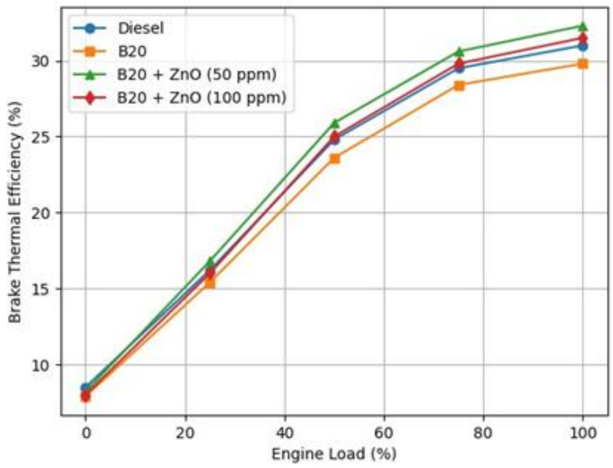

Figure 3. BTE Vs Load

4.2 Brake Specific Fuel Consumption (BSFC)

Brake Specific Fuel Consumption (BSFC) represents the amount of fuel consumed per unit brake power output and is an important parameter for evaluating fuel economy in compression ignition engines. The variation of BSFC with engine load for Diesel, B20, B20 + ZnO (50 ppm), and B20 + ZnO (100 ppm) shows a decreasing trend with increasing load for all tested fuels. At lower load conditions (0–25%), BSFC values were comparatively higher due to incomplete combustion, lower in-cylinder temperature, and higher relative heat losses. Among the tested fuels, neat B20 exhibited the highest BSFC because of its lower calorific value and higher viscosity compared to diesel, leading to slightly higher fuel consumption to produce the same brake power. As the load increased from medium to full load (50–100%), BSFC decreased significantly for all blends. This reduction is attributed to improved combustion efficiency, better atomization, and higher combustion temperature at increased load conditions. Diesel showed lower BSFC than neat B20 across all loads due to its superior fuel properties. The addition of ZnO nanoparticles to B20 resulted in a noticeable reduction in BSFC compared to neat B20. The B20 + ZnO (50 ppm) blend exhibited the lowest BSFC among all tested fuels at higher loads. This improvement can be attributed to enhanced catalytic combustion, improved heat transfer, and reduced ignition delay caused by the high surface area and oxygen buffering capability of ZnO nanoparticles. The improved combustion process allows more complete fuel utilization, thereby reducing fuel consumption per unit power output. Although the B20 + ZnO (100 ppm) blend also demonstrated reduced BSFC compared to neat B20, its performance was slightly inferior to the 50 ppm blend at full load. This may be due to minor agglomeration or slight changes in fuel properties at higher nanoparticle concentration, which can marginally influence atomization and combustion characteristics. Overall, the results indicate that the incorporation of ZnO nanoparticles enhances fuel economy, with 50 ppm identified as the optimal concentration for minimizing BSFC while maintaining stable engine operation [11].

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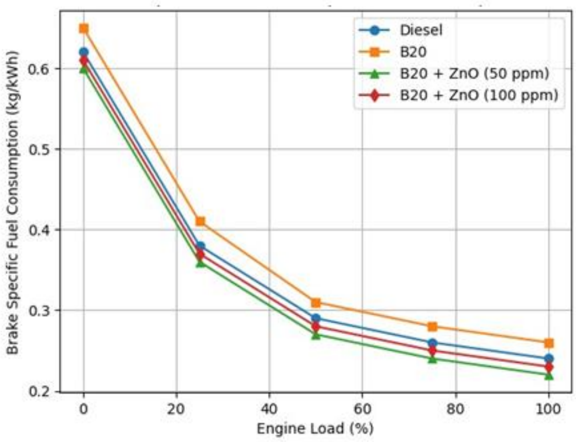

Figure 4 **BSFC vs Load**

4.3 Carbon Monoxide (CO) Emissions

Carbon monoxide (CO) emissions are primarily formed due to incomplete combustion of fuel under oxygen-deficient conditions. The variation of CO emissions with engine load shows a decreasing trend for all tested fuels. At lower loads, CO emissions were relatively higher because of lower in-cylinder temperature and incomplete oxidation of fuel. As the load increased, combustion temperature improved, leading to more complete oxidation and reduced CO levels. Among the tested fuels, neat diesel exhibited comparatively higher CO emissions than biodiesel blends due to the absence of inherent oxygen in its molecular structure. The B20 blend showed lower CO emissions because of its oxygenated nature, which promotes better combustion. The addition of ZnO nanoparticles further reduced CO emissions significantly. The B20 + ZnO (50 ppm) blend showed the lowest CO emissions across all loads. This reduction is attributed to the catalytic oxidation activity and oxygen buffering capability of ZnO nanoparticles, which enhance the conversion of CO into CO_2. The 100 ppm blend also reduced CO emissions compared to neat B20, but slightly higher values than 50 ppm were observed, possibly due to minor agglomeration effects at higher concentration [12].

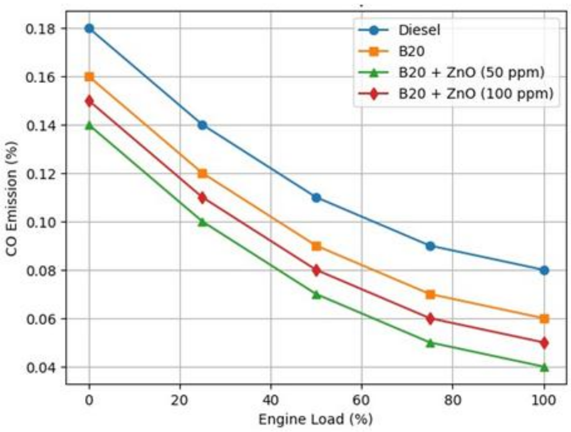

Figure 5 CO Emission Vs Load

4.4 Hydrocarbon (HC) Emissions

Hydrocarbon (HC) emissions represent unburned fuel particles escaping the combustion chamber. The HC emissions decreased progressively with increasing engine load for all fuels due to improved combustion efficiency at higher temperatures. Diesel showed higher HC emissions compared to biodiesel blends, mainly because biodiesel contains built-in oxygen that supports more complete combustion. The B20 blend demonstrated reduced HC emissions relative to diesel. The incorporation of ZnO nanoparticles further decreased HC levels. The B20 + ZnO (50 ppm) blend exhibited the lowest HC emissions, indicating enhanced oxidation of unburned hydrocarbons. The nanoparticles promote faster flame propagation and shorten ignition delay, leading to more complete fuel combustion. Although the 100 ppm ZnO blend also showed improvement over neat B20, its HC emissions were slightly higher than the 50 ppm blend at higher loads. This suggests that 50 ppm provides optimal dispersion and catalytic efficiency [13].

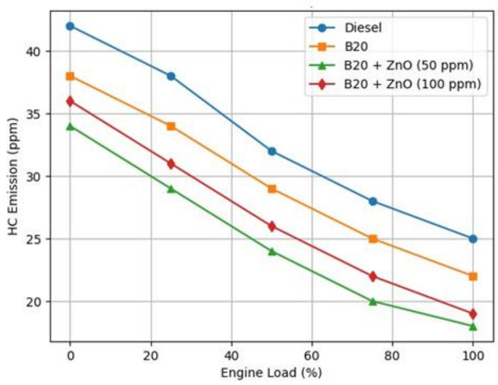

Figure 6 HC Emission Vs Load

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4.5 Nitrogen Oxides (NOx) Emissions

Nitrogen oxides (NOx) are primarily formed at high combustion temperatures and in the presence of excess oxygen. The NOx emissions increased with increasing engine load for all tested fuels due to higher in-cylinder temperature and pressure. B20 showed slightly higher NOx emissions than diesel because of its oxygen content and improved combustion characteristics. The addition of ZnO nanoparticles further increased NOx emissions marginally. The B20 + ZnO (50 ppm) and B20 + ZnO (100 ppm) blends exhibited higher NOx levels compared to neat B20, especially at higher loads. This increase can be attributed to enhanced combustion efficiency and elevated peak flame temperature caused by catalytic activity of ZnO nanoparticles. The 100 ppm blend showed slightly higher NOx than the 50 ppm blend, indicating that higher nanoparticle concentration may intensify combustion temperature, promoting NOx formation [14].

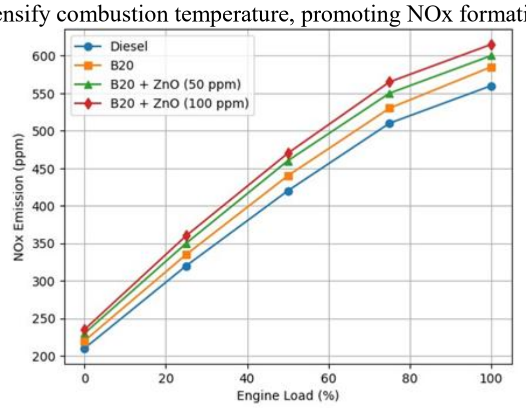

Figure 7 NOx Emission Vs Load

4.6 Smoke Opacity

Smoke emissions indicate the presence of soot particles formed due to incomplete combustion. Smoke opacity increased with engine load for all fuels because higher fuel injection at full load promotes rich combustion zones and soot formation. Diesel exhibited the highest smoke opacity among all tested fuels. The B20 blend showed reduced smoke due to its oxygenated structure, which supports soot oxidation. The addition of ZnO nanoparticles significantly reduced smoke emissions. The B20 + ZnO (50 ppm) blend demonstrated the lowest smoke opacity across all load conditions. This reduction is attributed to the catalytic oxidation of soot particles by ZnO nanoparticles and improved air–fuel mixing. Although the 100 ppm blend also reduced smoke compared to neat B20, the 50 ppm concentration provided slightly better performance, likely due to optimal dispersion and minimized agglomeration [15].

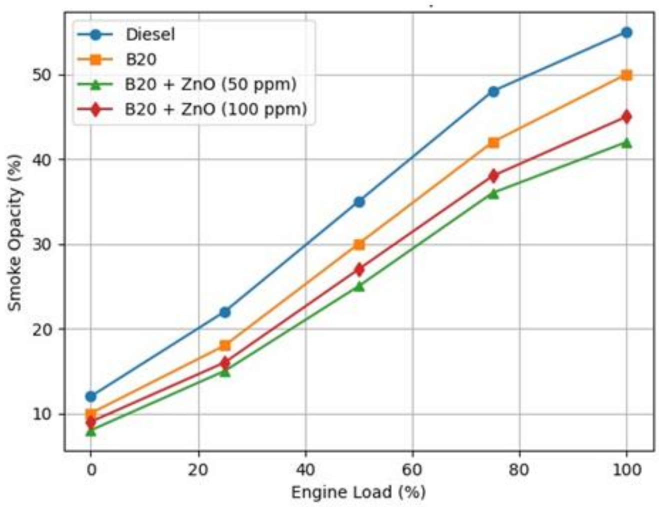

Figure 8 Smoke Emission Vs Load

Conclusion

The present experimental investigation evaluated the influence of zinc oxide (ZnO) nanoparticles on the performance and emission characteristics of a compression ignition engine fueled with B20 biodiesel blend. Based on the experimental results and detailed analysis, the following conclusions are drawn:

- The addition of ZnO nanoparticles significantly enhanced brake thermal efficiency (BTE) compared to neat B20. Among the tested concentrations, the B20 + ZnO (50 ppm) blend exhibited the highest efficiency across medium and full load conditions. The improvement in BTE is attributed to enhanced catalytic combustion, improved atomization, reduced ignition delay, and better heat release characteristics resulting from the high surface area and oxygen buffering capacity of ZnO nanoparticles.
- Brake specific fuel consumption (BSFC) decreased with the incorporation of ZnO nanoparticles. The 50 ppm blend demonstrated the lowest BSFC, indicating improved fuel economy and better energy conversion efficiency. Although the 100 ppm blend also showed improvement compared to neat B20, its performance was slightly inferior to the 50 ppm blend, likely due to minor agglomeration and marginal changes in fuel properties at higher concentration.
- Regarding emission characteristics, significant reductions in carbon monoxide (CO), hydrocarbons (HC), and smoke opacity were observed with ZnO nanoparticle addition. The B20 + ZnO (50 ppm) blend showed the most pronounced reduction in CO, HC, and smoke emissions due to enhanced oxidation reactions and improved combustion completeness. However, a marginal increase in nitrogen oxides (NOx) emissions was observed for nanoparticle-blended fuels, particularly at higher loads. This increase is primarily attributed to elevated in-cylinder temperature and improved combustion intensity caused by catalytic activity.

- Overall, the experimental results confirm that ZnO nanoparticles act as effective combustion-enhancing additives for biodiesel blends. The 50 ppm concentration was identified as the optimal dosage, providing a balanced improvement in performance and emission reduction without significant adverse effects. Therefore, ZnO nano-additized biodiesel can be considered a promising alternative fuel strategy for improving CI engine efficiency and reducing harmful exhaust emissions.

Future work may focus on long-term engine durability analysis, nanoparticle stability assessment, optimization techniques for emission control, and investigation under advanced injection systems such as CRDI engines.

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