

Experiment investigating the effect of ZnO nano-particles on diesel engine performance and emissions

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ABSTRACT

This analytical study examines the synergistic effects of (ZnO) Nano-particles as fuel additives on the performance and emission characteristics of conventional diesel engines. Various concentrations of ZnO nanoparticles, varying from (50–200 ppm), were systematically blended with standard diesel fuel using advanced homogenization techniques, including ultra-sonication and magnetic stirring. Experimental trials were conducted on a single-cylinder, four-stroke diesel engine operating at a constant rotational speed under variable load conditions. The findings reveal a significant improvement in combustion efficiency attributable to the catalytic properties and oxygen-enhancing effects of the Nano-particles, which promote more complete fuel oxidation. The optimal nanoparticle concentration of 200 ppm yielded a maximum increase in η_{Bth} alongside a notable reduction in SFC. Additionally, substantial decreases were observed in the emissions of carbon monoxide, unburned hydrocarbons, and nitrogen oxides, although carbon dioxide emissions increased as a consequence of enhanced combustion completeness. The study concludes that ZnO Nano-particles represent a promising catalytic additive for diesel fuels, contributing to improved thermal efficiency and reduced environmental impact.

Keywords: ZnO – nanoparticle, diesel engine performance, emission reduction, nanoparticle additives, four stroke.

INTRODUCTION

Diesel engine emissions pose a major environmental challenge due to their contribution to air pollution and climate change, including (NO_x), particulate matter (PM), and carbon monoxide (CO) [1–3]. Simultaneously, the demand for improved fuel efficiency to reduce reliance on fossil fuels is rising [4–5]. This necessitates the development of innovative fuel additives to address these issues. Metallic nanoparticles, such as zinc oxide (ZnO), offer a promising solution for enhancing fuel combustion properties due to their catalytic activity, large surface area, and ability to improve heat transfer, resulting in more complete combustion and reduced harmful emissions [6]. For instance, a recent study demonstrated that adding 100 ppm of ZnO Nano-particles

to a diesel fuel blend with recycled plastic oil (WPO20) reduced smoke emissions by 11.86%, NO_x by 14.93%, and improved thermal efficiency by 2.47% [7]. Similarly, nanoparticle-doped bio-diesel fuels, like lemongrass and soybean bio-diesel, exhibit improved combustion characteristics and lower CO and unburned hydrocarbon (UHC) emissions [8–10]. Prior research indicates that nanoparticle additives improve fuel's physicochemical properties, such as increased thermal conductivity and reduced viscosity, enhancing fuel atomization and air-fuel mixing [11]. For example, a study on ZnO-blended diesel fuel reported up to 28% reduction in UHC and 5.7% in CO emissions [12]. Other studies highlight nanoparticles' catalytic role in lowering soot ignition temperatures [13]. Recent advancements in Nano-fuel additives have highlighted their potential to

enhance diesel engine efficiency and reduce emissions [14–15]. Building on this, experimental and numerical analyses were conducted to evaluate diesel blends with ZnO nanoparticles (0.025%, 0.05%, 0.1%) under full-load conditions at 2000–3000 rpm. The 0.1% ZnO blend demonstrated optimal performance: at 2500 rpm, (η_{Bth}) rose by 11.7%, while (SFC), exhaust temperature, NOx, and CO₂ emissions decreased by 1.67%, 11.4%, 10.67%, and 7.6%, respectively. Cylinder pressure increased by 2.3%, attributed to improved combustion kinetics. Numerical simulations Diesel-RX software validated experimental trends, underscoring the blend's efficacy in enhancing combustion efficiency and reducing pollutants. These findings align with prior studies on metal oxide nanoparticles as demonstrated by Rajak et al. [16] and advance the discourse on sustainable fuel technologies by quantifying ZnO's role in emission mitigation and performance optimization. Specifically, Hamadi et al. [17] found that the use ZnO at levels of 50 and 100 ppm improves (η_{Bth}) and reduces BSFC compared to standard diesel fuel. Emission analysis reveals that ZnO-blended fuels produce lower levels of NOx and smoke across all loads, while HC and CO emissions are higher from diesel fuel at high loads but lower at low loads. While Ibrahim et al. [18] demonstrated that zinc oxide nanoparticles (ZONPs) blended into diesel fuel via ultra-sonication and mechanical homogenization significantly improved engine performance and emissions characteristics at a constant engine speed of 1400 rpm and under varying loads. while Gursel [19] found that adding $ZnFe_2O_4$ and $ZnCO_3$ nanoparticles (100 ppm) to diesel fuel improved (η_{Bth}) and reduced CO emissions in a heavy-duty diesel engine (11.670 cc) tested at 600 rpm under varying loads (250–380 Nm). Recent studies have explored the incorporation of nanoparticle (NP) additives into diesel fuel to improve engine performance and reduce emissions. Deresse et al. [20] studied the incorporation of nanoparticles such as $NiZnFe_2O_4$ and CeO_2 with oxygenated fuels (ethanol and acetone) to enhance the efficiency of diesel engines and reduce emissions. Rico et al. [21] found that (ZnO) and goethite (GOE) as effective additives to palm biodiesel improve diesel engine performance and emission levels. While palm-derived fine zinc oxide (PPaOZnO) particles improved mist penetration and reduced smoke opacity by 60% compared to diesel, as reported by Rohit et al. [22]. Anbarasu et al. [23] and Manzoore et al.

[24] demonstrated the ability of ZnO Nano-particles to improve biodiesel blends (canola/mahua), enhancing thermal efficiency (9.65–16.4%) and reducing emissions of nitrogen oxides, carbon monoxide, and hydrocarbons (5–24.8%) through improved combustion dynamics. The pursuit of enhanced thermal and energy efficiency unites diverse engineering applications, from internal flow systems to combustion engines. The principles of heat transfer augmentation, as demonstrated in dimpled pipe flows and thermal storage strategies, find a parallel in the combustion process through the use of nano-additives. This study extends that foundational concept by investigating the introduction of zinc oxide nanoparticles into diesel fuel, aiming to similarly disrupt and optimize the combustion environment for enhanced efficiency and lower emissions [25–26]. In this study object to assess the effect of the added ZnO Nano-partical in diesel engine combustion on performance and emission behaviors under various load and constant speed.

NOVELTY IN CURRENT WORK

This research introduces a groundbreaking approach by integrating ZnO nanoparticles into traditional diesel fuel, aiming to enhance both efficiency and lower emissions. This marks a significant shift from earlier studies that primarily concentrated on biodiesel mixtures. By fine-tuning the concentration of ZnO (between 50 and 200 ppm) and utilizing sophisticated dispersion methods like ultrasonication and magnetic stirring, this study effectively navigates the inherent performance-emission trade-offs associated with diesel fuel, including metrics like brake thermal efficiency (η_{Bth}) and (SFC), as well as emissions of CO, NOx, and HC. The innovation lies in showcasing the dual catalytic and thermodynamic functions of ZnO within diesel systems, addressing a notable gap in the research surrounding nanoparticle interactions with diesel fuel. The results provide scalable and retrofit-friendly approaches for aging diesel engines, leading to the advancement of sustainable fuel technology.

MATERIALS AND METHODS

A single-cylinder TD111 diesel engine was used for the experiments, which were run at 2000

rpm with incremental loads ranging from 20% to 60%. Four ZnO-diesel blends (50–200 ppm) were prepared using ultrasonication and magnetic stirring. Analysis was done on the fuel's density at 15 °C using a digital density meter according to ASTM D4052, viscosity at 40 °C using a capillary viscometer according to ASTM D445, heating value measured using a bomb calorimeter according to ASTM D240, and cetane number using a cetane engine device according to ASTM D613 (Table 1).

Preparation of nanoparticle ZnO

In this study, zinc oxide (ZnO) nanoparticles were introduced into conventional diesel fuel at varying concentrations (50, 100, 150, and 200 parts per million). The nanoparticle-diesel blends were synthesized using a two-step homogenization process: magnetic stirring (30–45 minutes) followed by ultra-sonication to ensure even distribution of nanoparticles within the base fuel (Figure 1). Post-blending, the fuel samples were allowed to equilibrate to ambient temperature prior to engine testing. The physicochemical properties of the pristine ZnO nanoparticles, including particle size, density, and thermal stability, are detailed in Table 1. To evaluate nanoparticle morphology, scanning

electron microscopy (SEM) was conducted, with representative micrographs of the ZnO nanoparticles and their size distribution presented in Figure 2 (Panels A and B). This methodological approach ensured consistency in nanoparticle integration and facilitated a systematic investigation of concentration-dependent effects on engine enactment and emissions (Table 2).

EXPERIMENTAL SETUP

Experimental investigations were carried out using a single-cylinder, 4-stroke engine (model TD111) equipped with air-cooled system and direct fuel injection mechanism. The engine, featuring a piston combustion chamber bowl, was operated under controlled conditions at the Internal Combustion Engine Laboratory within Kufa, Iraq. Critical operational parameters of the engine, including bore diameter (0.70 m), stroke length (0.65 m), swept volume (0.25 L), max rotational speed (4000 rpm), and total weight (45 kg), are comprehensively outlined in Table 3.

Testing protocols involved evaluating four distinct ZnO-diesel fuel blends under

Table 1. Thermal properties of nano-diesel blends

Sample	Density (kg/m ³)	Viscosity (mm ² /s)	Flashpoint & firepoint °C	Heating value (kJ/kg)	Cetane number
Pure diesel	828	3.63	40–70	42968	52
50 ppmZnO+Di	912	4.18	50–76	41564	58
100 ppmZnO+Di	913	4.21	50–78	41623	58
150 ppmZnO+Di	915	4.32	55–79	41895	60
200 ppmZnO+Di	918	4.49	60–82	42064	61

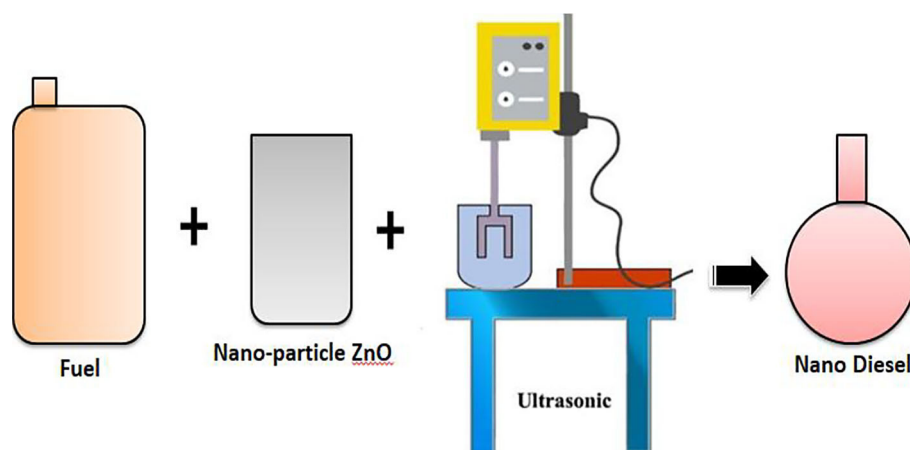


Figure 1. Schematic layout of the experimental setup

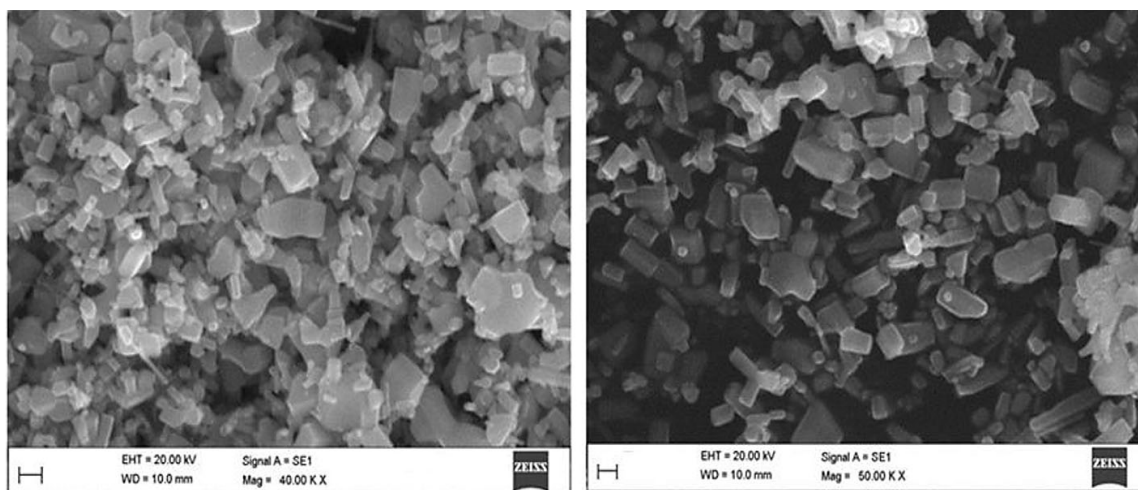


Figure 2. Electron micrographs of (a) zinc oxide nanoparticles (b) nanoparticle size [27]

Table 2. Properties of Nano-ZnO

Item	Specifications
Chemical name	Zinc oxide (ZnO) nanoparticles, 99.8%, USA
Density	5606 kg/m ³
Mean particle size	10–30 nm
Aspect	White powder
Fusion point	1975 °C
Vaporization point	2300 °C
BET surface area (SSA)	> 10 m ² /g

Table 3. Engine specifications[28]

Engine parameters	Specification
Model	TD111
General	Air cooled, variable speed, CI, 4-stroke, and single-cylinder
Fuel	Diesel
Bore @ stroke	0.70 m @ 0.65 m
Displacement volume	0.000250 m ³
Maximum speed	4000 rpm
Weight	45 kg

steady-state engine speed conditions to systematically analyze their effects on performance metrics and exhaust emissions. Load conditions were incrementally varied (20–60%) to simulate real-world operational stresses. The experimental rig, illustrated in Figure 3, incorporated precision instrumentation to monitor combustion dynamics, fuel consumption, and emission profiles, ensuring reproducibility and accuracy in data acquisition. This methodology enabled a methodical assessment of nanoparticle-enhanced fuels under standardized testing frameworks, aligning with established practices in combustion research.

The exhaust gas analyzer

The HPC501 Exhaust Gas Analyzer is an essential tool for understanding and optimizing the performance and emissions. It provides valuable data that can be used to make adjustments and improvements, leading to more efficient and environmentally friendly engine

operation. The meter is designed to measure the concentration of various gases present in vehicle exhaust, including HC, CO, CO₂, O₂, and NOx (Figure 4). This is achieved by placing an exhaust gas sensor in the exhaust pipe, which allows for accurate and real-time measurements. By analyzing these gas concentrations, it can provide valuable insights into engine combustion performance and emission levels.

RESULTS AND DISCUSSION

The primary aim of this investigation was to evaluate the impact of Nano ZnO as fuel additives on the operational features of a compression ignition diesel engine. The study systematically assessed the effects of varying Nano-particle concentrations on key performance indicators, including Bsf, η_{bth} , and exhaust emission factors – specifically (CO₂, CO, HC, and NOx).

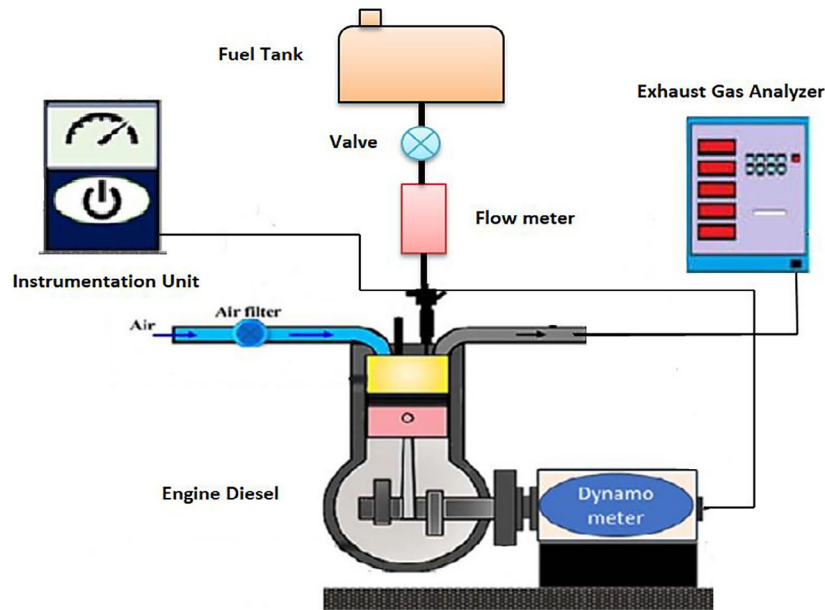


Figure 3. Experimental rig diagram



Figure 4. The exhaust gas analyzer

Engine performance

Experimental results in Figure 5 demonstrate enhanced thermal efficiency with ZnO nanoparticle additives (50–200 ppm) in diesel fuel

under increasing loads. The 100ppm ZnO+Di blend achieved optimal gains (7–12%), while higher concentrations (200 ppm) reduced improvements (5–9%). ZnO's high thermal conductivity and surface area-to-volume ratio enhance heat transfer and combustion kinetics, improving fuel-air mixing and reaction rates. This reduces thermal losses and promotes energy-efficient combustion. The decline in efficiency gains beyond 100 ppm is attributed to nanoparticle agglomeration, which disrupts combustion stability. A critical threshold (~100 ppm) balances efficiency and stability, aligning with Nano additive behavior in fuel systems. This is consistent with previous studies [29]. The results shown in Figure 6 demonstrated a significant reduction in fuel consumption (Bsfc) with increasing zinc oxide (ZnO) concentration in diesel, where 200 ppm ZnO-enriched diesel achieved the

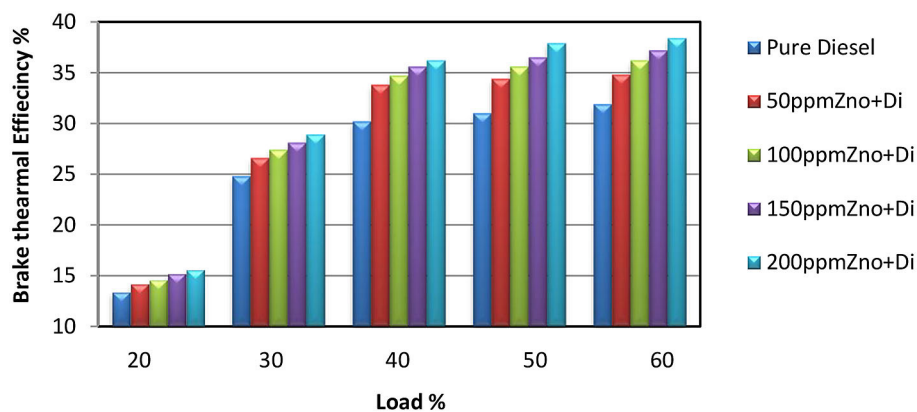


Figure 5. Thermal efficiency of diesel engine with ZnO nanoparticles at different loads

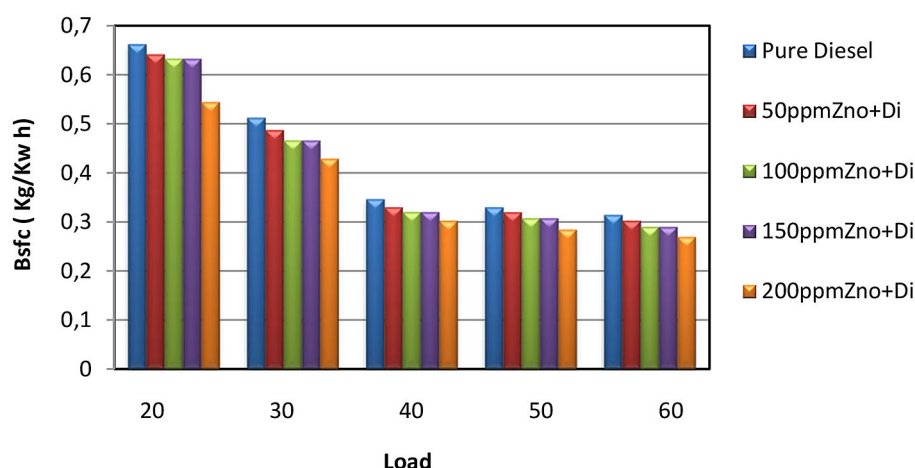


Figure 6. Bsfc of diesel engine with ZnO nano-particles at different loads

highest improvement of ~16.7% compared to pure diesel. This enhancement is attributed to ZnO's catalytic role in improving combustion efficiency by reducing heat loss and enhancing oxygen transfer, thereby minimizing incomplete fuel combustion. Improvements were most pronounced at higher loads, with a 12–17% reduction, indicating a synergistic interaction between ZnO concentration and load intensity. These findings support ZnO as an effective additive for optimizing diesel engine performance [30]

Interlinked emissions in combustion processes and environmental impact

The Figure 7 demonstrates CO₂ emission trends for pure diesel and ZnO-blended diesel (50–200 ppm) across varying loads (20–60). Optimal ZnO concentration (150–200 ppm): Achieves a ~10–15% reduction in CO₂ emissions compared to pure diesel under high load (60), attributed to

ZnO's catalytic enhancement of combustion efficiency. This range likely represents a saturation point for additive effectiveness. Higher loads (e.g., 60) show ~5–7% greater emission reduction than lower loads (20–30) for the same ZnO concentration, suggesting intensified catalytic activity under operational stress.

The Figure 8 shows indicating CO emissions—for pure diesel and ZnO-blended diesel (50–200 ppm) under varying loads (20–60). ZnO additives reduce emissions decreases progressively with higher ZnO concentrations. For example, at 200 ppm ZnO, emissions drop from 1.2% (pure diesel) to 0.2%, reflecting a ~83% improvement. Lower loads (e.g., 20–40) show gradual reductions, while higher loads (50–60) amplify ZnO's effectiveness, likely due to enhanced combustion efficiency under stress. The dramatic emission reduction (e.g., ~66–83% across 50–200 ppm ZnO) stems from ZnO's catalytic properties, which suppress soot formation by promoting complete

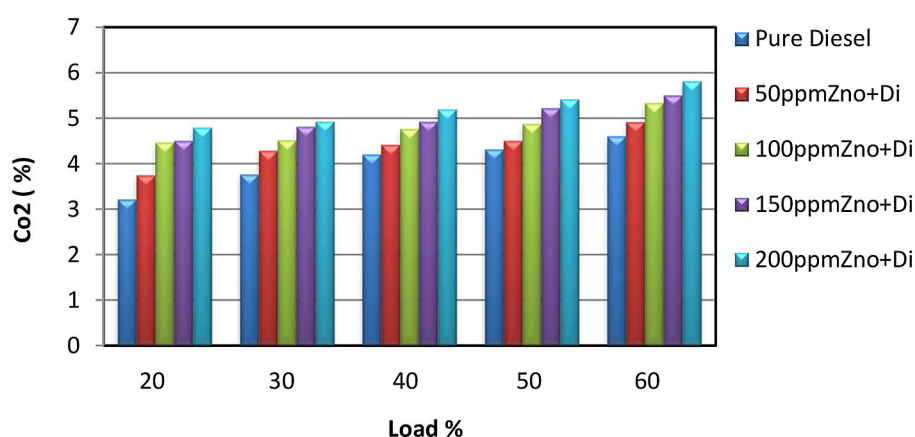


Figure 7. CO₂ emission percentage of diesel engine with ZnO nanoparticles at varied loads

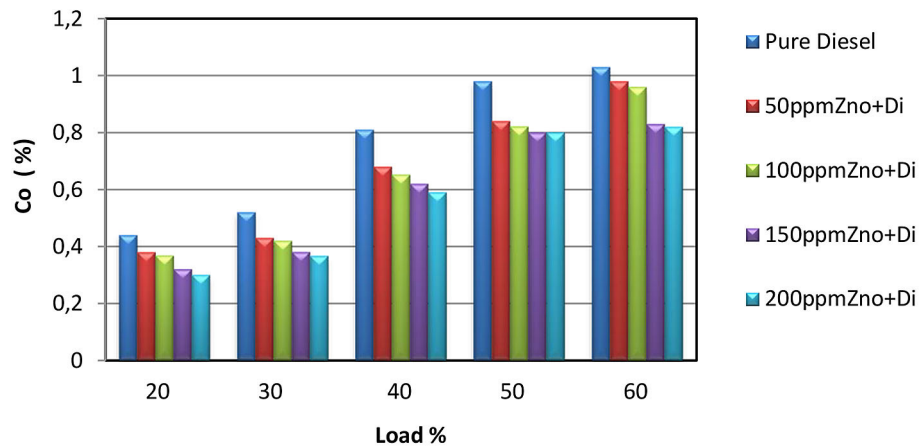


Figure 8. Effects of concentration of ZnO nano-particles on (CO) under different

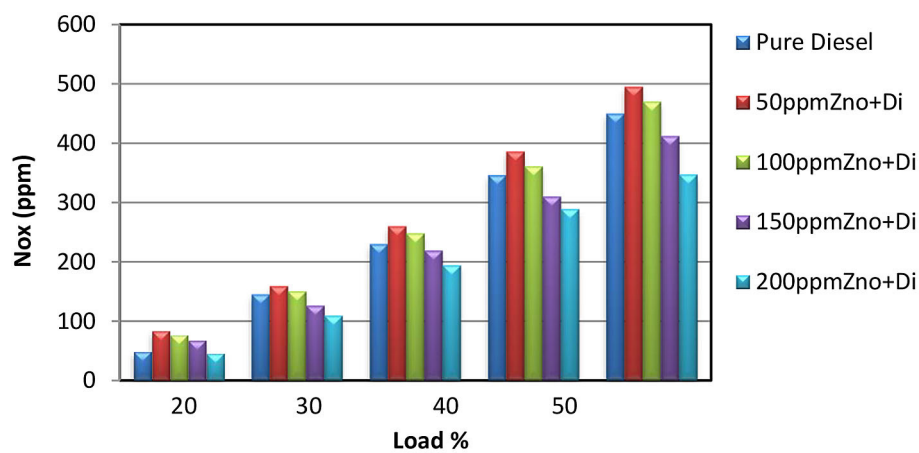


Figure 9. NOx emissions vs. load for diesel with ZnO+Di additives

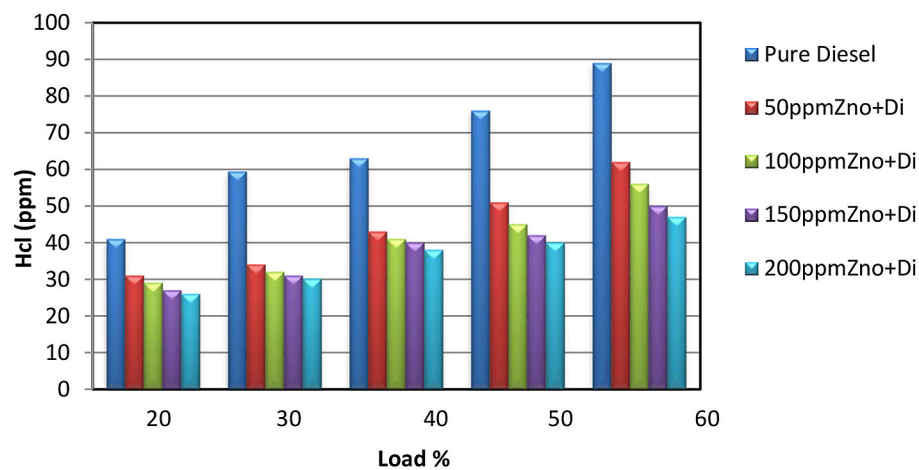


Figure 10. HC emissions vs. load for diesel with ZnO+Di additives

oxidation. The saturation effect at 150–200 ppm suggests optimal catalytic activity. These results align with studies on metal oxide additives mitigating diesel emissions [31], positioning ZnO as a viable solution for sustainable fuel engineering.

The Figure 9 illustrates nitrogen oxides (NOx) emissions (ppm) versus engine load (20–60%) for diesel fuel blended with varying concentrations of saturated zinc oxide (ZnO) additives (50–200 ppm). Key findings reveal a progressive reduction in NOx

emissions with increasing ZnO concentration. At 200 ppm ZnO, NO_x levels decreased by approximately 18–22% across all loads compared to pure diesel, with the highest improvement observed at intermediate loads (40–50%). ZnO nanoparticles likely act as catalytic agents, moderating combustion temperatures and suppressing thermal NO_x. The diminishing improvement rate beyond 150 ppm suggests saturation effects, where additional ZnO particles no longer enhance catalytic activity efficiently. The NO_x reduction rate peaked at 150 ppm ZnO (15–19% improvement), with marginal gains (< 3%) at 200 ppm. This indicates an optimal ZnO concentration range (100–150 ppm) for balancing efficacy and cost-effectiveness. This concise analysis aligns with environmental engineering priorities and provides actionable insights for optimizing emission control strategies [32].

Figure 10 depicts hydrogen chloride (HCl) emissions (ppm) versus engine load for diesel fuel blended with saturated zinc oxide (ZnO) additives (50–200 ppm). HCl levels decrease systematically with higher ZnO concentrations, showing a 25–35% reduction at 200 ppm ZnO compared to pure diesel, particularly pronounced at higher loads (50–60%). ZnO nanoparticles likely neutralize HCl via surface reactions (e.g., $\text{ZnO} + 2\text{HCl} \rightarrow \text{ZnCl}_2 + \text{H}_2\text{O}$), reducing acidic emissions. Enhanced dispersion at moderate concentrations (100–150 ppm) improves reactivity, while agglomeration at 200 ppm may limit further gains. Optimal reduction occurs at 150 ppm ZnO (28–32% improvement), with marginal returns (<5%) at 200 ppm, suggesting saturation of active sites. This identifies 100–150 ppm ZnO as the cost-effective range for HCl mitigation, aligning with sustainable emission control strategies. These findings highlight ZnO's dual role in curbing NO_x and HCl emissions, advocating its integration into cleaner diesel formulations. The results are consistent with previous studies [33].

CONCLUSIONS

The operation and exhaust outputs of diesel engines were experimentally studied using ZnO Nano-particles added to the fuel. According to the research, the Nano-diesel mixture had more stability. The conclusions are as follows:

1. The (η_{Bth}) increases with increasing Nano-diesel fuel blend proportion. The greatest magnitude of (η_{Bth}) was seen at (200ppmZnO+ Di) at

load 60% with constant engine speed of 2000 rpm, with an improvement of 12% compared to pure diesel fuel.

2. Adding ZnO illustrates the extreme reduction of 16.7% in (Bsfc) detected at 60% load and (200ppmZnO+Di) blend comparison with pure diesel.
3. Increasing the blend amount of the Nano-particles (ZnO) 50–200ppm by weight at constant speed and various loads to reduce the (35% HCl, 22%NO_x, and 1.2CO) releases.
4. The sample 200 ppm has emitted more CO₂ emission when compared with pure diesel tested in the engine due to more amount of ZnO.

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