International Research Journal of Multidisciplinary Scope (IRJMS), 2025; 6(4):1351-1361

Original Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2025.v06i04.07236

Nano Catalyst Impact on Exergy Analysis of CI Engine with Diesel–CuO, Gr and Al_2O_3 Blends

Prabhat Patel*, Abhishek Shrotriya, Gourav Patel

Medicaps University, Indore, Madhya Pradesh, India. *Corresponding Author's Email: uit.prabhat@gmail.com

Abstract

This study examines how copper oxide (CuO), graphene (Gr) and aluminium oxide (Al_2O_3) nanoparticles affect diesel engine performance and fuel economy. Nanoparticles are combined with diesel fuel and surfactants before engine testing. The results suggest that adding nanoparticles to diesel increases engine performance, brake thermal efficiency (BTE) and reduces brake specific fuel consumption (BSFC). In this study, the second law of thermodynamics, based on exergy and entransy theory, was used to analyze the energy output of a diesel engine fueled with additives for diesel Nano catalysts at five different concentrations (0.05, 0.44, 1.025, 1.6 and 2 g/l), including Al_2O_3, CuO, and Gr nanoparticles. The trials were run with varying engine speed from 1500-2500 rpm at full load. The findings of this investigation demonstrated that adding nanoparticles to diesel decreased BSFC while increasing BTE. Reductions were made in the heat loss from cooling water, unaccounted heat loss and heat loss from exhaust gases. The BTE, exergy efficiency and entransy efficiency went up by an average of 12.35%, 7.5% and 18.5% when specific nanoparticles were added to pure diesel blends at a rate ranging from 0.05 to 2 grams per liter. Additionally, BSFC, entropy generation, exergy destruction and entransy destruction all had average decreases of 11, 5.5, 7.5 and 18.5%. At an engine speed of 2100 rpm, the nano-Gr-diesel containing 1.6 g/l nanocatalyst had the maximum energy efficiency and minimum exergy loss compared to other diesel nano-catalyst-blend.

Keywords: Combustion, Engine Performance, Entransy, Exergy, Nanoparticles.

Introduction

Researchers have been looking for new energy sources for the past several decades to make energy conversion equipment and systems work better and to cut down on the dangerous pollutants that come from generating energy (1). Diesel engines are still very important for producing energy and for use in industry today (2). This is because they are very fuel-efficient, long-lasting, and reliable. However, using regular diesel fuel causes big problems for the environment, such as more nitrogen oxides (NOx), carbon monoxide (CO), and unburnt hydrocarbons (UHC). These pollutants make the world warmer, cause acid rain, and hurt people's health. Researchers have suggested replacing regular diesel with better fuels that include catalytic additives in order to solve these problems while still getting the benefits of diesel engines (1–4). In recent years, there has been a lot of interest in using hydrocarbon-based and metal oxide nanoparticle additions. These additives have been demonstrated to increase combustion, lower emissions, and make fuel work better overall (5, 6). Aluminum oxide (Al_2O_3), copper oxide (CuO), and graphene (Gr) are the nanoparticles that have been investigated the most in diesel mixes. This is because they contain oxygen, have high thermal conductivity, and can act as catalysts (7–10). These nanoparticles make gasoline burn better by speeding up oxidation processes, moving heat around, and moving mass around inside the engine cylinder as shown in Figure 1. They also speed up the ignition process and keep the combustion stable, which makes the burning of fuel more complete and efficient as shown in Table 1. This dual impact not only improves brake thermal efficiency (BTE) but also cuts down on hazardous emissions of gases and particles (11). Nanoparticles as diesel fuel additives have become a potential solution to boost engine performance and meet environmental standards at the same time. Another way to meet stricter pollution rules is to make diesel engines work better while using less fuel (12). So, it is important to look at engine features in more depth than only the combustion characteristics, performance,and exhaust emission

(Received 28th July 2025; Accepted 01st October 2025; Published 31st October 2025)

Table 1: Mechanistic Role of Nanoparticles in Exergy Reduction of CI Engine

Nanoparticle	Combustion Kinetics	Heat Transfer	Impact on Irreversibility / Exergy
CuO	Acts as an oxygen buffer and catalyst, enhancing the oxidation of CO and unburnt HC and promotes faster combustion reactions.	Moderate assists indirectly via improved oxidation.	Reduces chemical irreversibility by improving combustion completeness, lowering exergy losses in exhaust gases. (4-5)
Graphene (Gr)	Provides active surface sites for fuel-air interactions, aids micro-level flame propagation.	Extremely high thermal conductivity enables uniform temperature distribution and faster heat dissipation.	Reduces thermal irreversibility by minimizing hot spots and entropy generation and improves thermal exergy efficiency. (10)
Al_2O_3	Enhances atomization, reduces ignition delay and induces micro explosions that accelerate combustion kinetics.	Good thermal stability supports consistent heat release without agglomeration.	Reduces combustion irreversibility by accelerating fuel oxidation rates, improving chemical to thermal exergy conversion. (11-12)

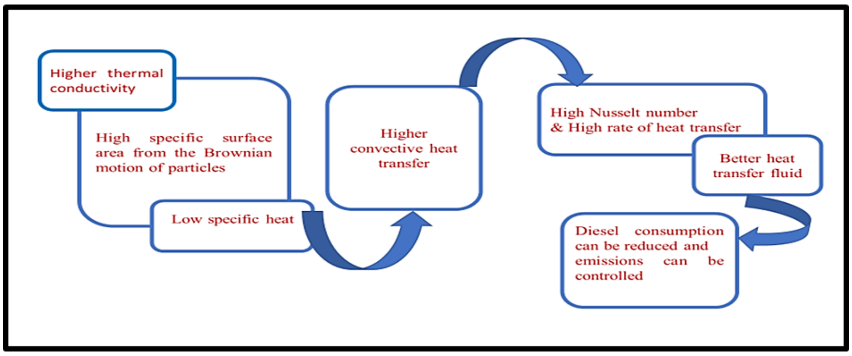

Figure 1: Effect of Nanoparticle Additive on Heat Transfer Parameter

(13). A lot of people use the first rule of thermodynamics to figure out how much energy internal combustion engines consume, but this method doesn't take into consideration the quality, recyclability, or sustainability of the fuel being used (14). Exergy analysis has become a useful tool for engineers to measure energy losses, figure out what causes irreversibility, and find subsystems in a diesel engine that aren't working as well as they should (15). The second rule of thermodynamics is the basis for exergy analysis. This law says that energy may be used to do productive work as well as be conserved. Exergy is the most beneficial work that a system can do when it is in equilibrium with the reference environment, which is commonly called the dead state (15). At the same time, entransy is a measure of how well a system can transmit heat. It is the most useful work that can be done with heat transfer when the system finds equilibrium with its reference state (15, 16). Irreversibility is the main reason why diesel engines lose efficiency. Both exergy and entransy tests provide us with useful information about how well internal combustion engines work thermodynamically (17). Experimental investigations have validated the efficacy of these analyses. For instance, the best gains in brake-specific fuel consumption (BSFC) were 8.5%, 10.9%, and 12.5% for CuO, Al_2O_3, and Gr-based nanodiesel fuels, respectively. The biggest increases in BTE were 8%, 13%, and 16%. Exergy-based tests also showed that exergy efficiency went up by 6.4%, 7.5%, and 9.8% for the same nanoparticle mixes. Entransy efficiency went up even more, by 13%, 18%, and 21%. Exergy destruction decreased by 5%, 6.3%, and 7.5%, while entransy destruction diminished by 9.4%, 11.5%, and 16.3% for CuO, Al_2O_3 and Gr nanodiesel fuels, respectively, in comparison to conventional diesel. These results show that nanodiesel fuels not only make energy and exergy performance better, but they also make the processes that change energy from one form to another better, especially at higher engine speeds (18-20). Consequently, the integrated application of the first and second principles of thermodynamics yields a more thorough comprehension of engine dynamics, facilitating researchers in detecting energy losses, measuring irreversibility, and assessing the sustainability characteristics of new fuel mixes (21).

This study is unique in integrating the mechanistic activities of CuO, Gr, and Al_2O_3 nanoparticles with a comprehensive exergy-based evaluation of a CI engine. This study examines how these nanoparticles' catalytic and thermal conductivity effect exergy destruction and energy usage, unlike most previous studies that focused on performance and emissions. Blend optimization methodically finds nanoparticle-diesel combinations that maximize exergy efficiency without affecting engine stability or emissions regulations (20). A comparative exergy analysis of CuO, Gr, and Al_2O_3-diesel blends sheds light on nanoparticle-specific catalytic mechanisms and their impact on chemical, thermal, and exhaust exergy efficiencies, and is rarely documented in the literature. The connection between nanoparticle functioning, mix optimization and stringent exergy evaluation in CI engine applications is novel (21).

The report acknowledges both the energy advantages and some practical issues. It may be difficult to use CuO, Gr, and AlO_3 on a large scale due to the high cost of combining them (22). Additionally, the mix may become less homogenous due to long-term stability problems such as nanoparticle aggregation (18). Additionally, hard nanoparticles may lead to engine wear, which emphasizes the need for additional research on cost-effectiveness and durability before their widespread usage.

A two-step procedure was employed to make the nano-diesel that was evaluated throughout this experiment. The catalyst SDS (Sodium dodecyl sulphate) was dissolved into the diesel fuel before adding nanoparticles and the sample was weighed using a weighing machine (3).

Figure 2: Ultrasonicator Process of Sample

Figure 3: Different Samples of Nanodiesel Containing

Al_2O_3, CuO and Gr NanoparticlesIn order to guarantee proper mixing and fluid stability nanodiesel is subjected to an ultrasonication machine after being combined with nanodiesel and catalyst for a predetermined amount of time (4, 5). After ultra-sonication nano-diesel is ready for additional examination and testing as shown in Figure 2 and 3.

Methodology

We examined Al_2O_3, CuO, and Gr nanoparticles in diesel fuel to see how they affected engine performance. Mixing nanoparticles with gasoline at a set ratio using ultrasound ensured that they were evenly spread out and did not stick together. This pretreatment procedure was needed to keep the fuel stable and keep the injectors from being blocked during combustion. The tests employed a Kirloskar diesel engine with four strokes, one cylinder, direct injection, and vertical cylinders. The engine had a stroke of 110 mm and a diameter of 80 mm. As illustrated in figure 4, it featured a compression ratio of 16.5:1, a fuel injection timing of 23° BTDC, and a power output of 5 kW. A water-cooled rope brake dynamometer was used to assess the engine load and braking power. Initially, the engine underwent testing with pure diesel to assess the impacts of nanoparticles. The studies for each fuel were done at different speeds (1500–2500 rpm) and with a full load (13). Once the engine had reached a steady state, measurements were taken for each test set. The studies were carried out with the test engine functioning at an ambient temperature of 30 ± 2ºC. Nanoparticle blended fuels as shown in Figure 3, were tested under the same conditions to see how they compared in terms of performance and emissions. We measured the brake thermal efficiency, brake specific fuel consumption, and heat release rate.

Results and Discussion

The way CI engines burn fuel and transfer heat is significantly impacted by the thermal conductivity, heat transfer coefficient, specific heat, and viscosity of nanoparticle-diesel blends. The addition of CuO, Gr and Al_2O_3 improves heat transfer and thermal conductivity while slightly altering viscosity and specific heat. This improves atomization, stabilizes combustion, and evens out the temperature distribution in the cylinder. The energy conversion process is improved by these property improvements. Exergy analysis reveals irreversibility, whereas thermal analysis displays the complete energy balance. When combined, they provide a comprehensive picture of how to raise performance and efficiency.

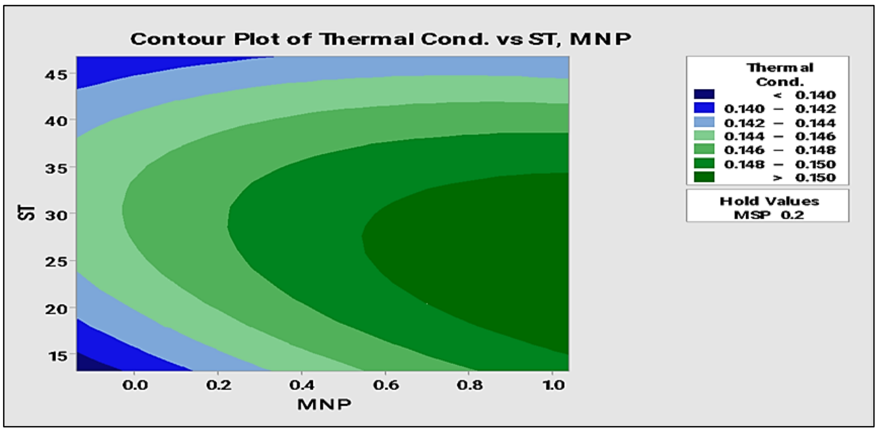

Figure 4: Effect of Sonication Time (ST) and Mass of Nanoparticle (MNP) on Thermal Conductivity

Figure 4 represents graphical analyses of the thermal conductivity behavior of a material shown as a function of two variables sonication time (ST) and mass of nanoparticle (MNP) with mass of surfactant (MSP) held constant at a value of 0.2g. It is a contour plot providing a two-dimensional view where lines of constant thermal conductivity (iso-thermal conductivity lines) are drawn on a plane defined by ST and MNP (6, 7). The plot shows regions with similar thermal conductivity values through color gradation, with darker greens and blues indicating lower thermal conductivity values and lighter shades representing higher values. This contour plot makes it easier to see the relationship between the variables, especially how thermal conductivity responds to changes in ST and MNP.

this plot is useful in understanding how thermal conductivity is influenced by the parameters ST and MNP allowing for better visualization and analysis of the materials thermal behavior under varying conditions (8).

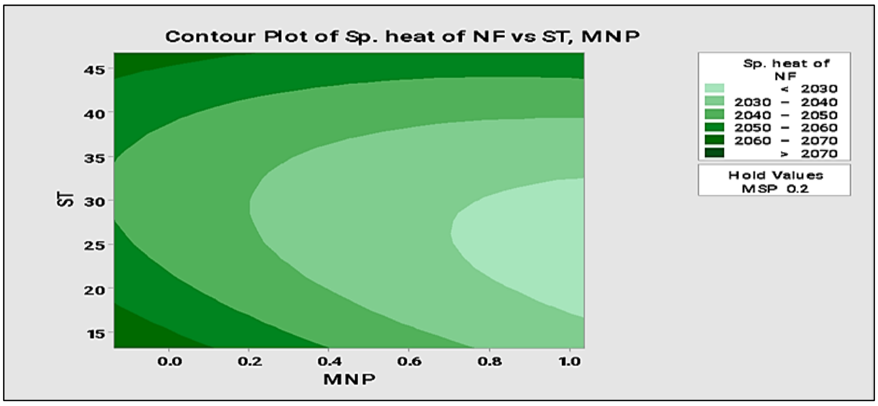

Figure 5: Effect of Sonication Time (ST) and Mass of Nanoparticle (MNP) on Specific Heat of Nano fluid

Figure 5 represents a surface plot that reveals how the specific heat of nanofluids varies with changes in ST and MNP with the mass of surfactant (MSP) held constant at a value of 0.2g. The surface appears to slope downward as MNP increases suggesting that higher MNP values are associated with a decrease in the specific heat of nanofluids. Conversely as ST increases the specific heat appears to level off indicating a more complex interaction between these variables (9). This plot provides a visual representation of how the specific heat of nanofluids is influenced by variations in ST and MNP offering insights into their combined effects (3, 10).

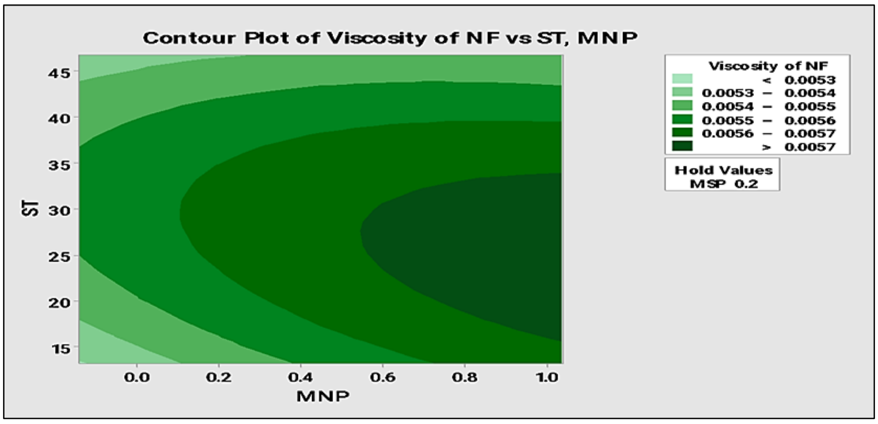

Figure 6: Effect of Sonication Time (ST) and Mass of Nanoparticle (MNP) on Heat Transfer Coefficient (HTC) of Nanofluid

The Figure 6 analyzes the relationship between heat transfer coefficient (HTC-h) and the variables sonication time (ST) and mass of nanoparticle (MNP) with mass of surfactant (MSP) held constant at a value of 0.2g/l. The Figure 6 represents the surface plot, where HTC(h) is plotted against ST on the vertical axis and MNP on the horizontal axis. The plot uses different shades of green to represent varying ranges of HTC(h) values. Lighter shades correspond to lower HTC(h) values, while darker shades indicate higher values. The plot suggests a gradual increase in HTC(h) as both ST and MNP increase (3, 11). While 3D surface plot presenting the same relationship between HTC(h), ST and MNP. Here the surface is depicted as a curved plane in a three-dimensional space. The vertical axis represents HTC(h) and the surface shows how HTC(h) changes with varying levels of ST and MNP. The curvature of the surface suggests a nonlinear relationship where HTC(h) increases more significantly at higher levels of ST and MNP. Both plots provide a visual representation of how HTC (h) varies with changes in ST and MNP offering different perspectives for better understanding of the data (12). The evaluations of thermal energy and exergy performance in a diesel engine concentrate on measuring both the magnitude and quality of energy conversion (13, 14). Thermal energy analysis assesses the comprehensive energy balance, encompassing the conversion of fuel energy into useful work, waste heat and losses via exhaust and cooling. In contrast exergy analysis evaluates the engine capacity to efficiently harness available energy by considering irreversibility, including friction, combustion inefficiencies and heat losses. Thermal energy elucidates engine efficiency, whereas exergy analysis reveals energy deterioration hence enhancing optimization of engine performance and minimizing inefficiencies (2, 15).

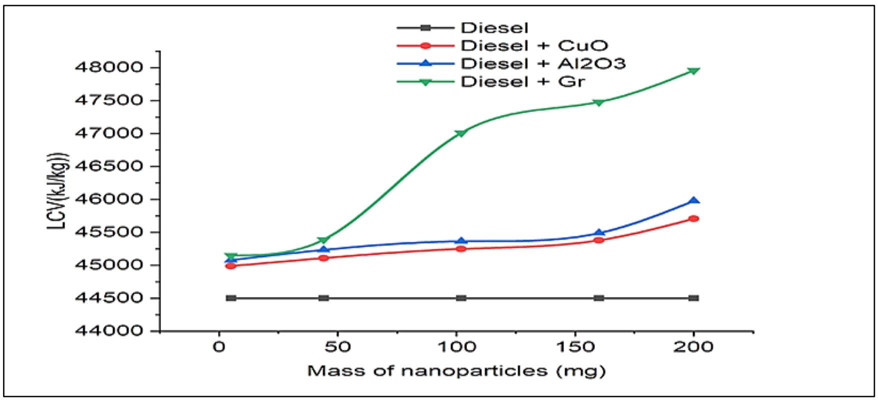

Figure 7: Effect of Mass of Nanoparticle on Lower Calorific Value of Nanodiesel Blend

Figure 7 illustrates the impact of adding different nanoparticles to diesel fuel on its Lower Calorific Value (LCV) measured in kJ/kg. It compares pure diesel with diesel mixed with copper oxide (CuO), aluminum oxide (Al_2O_3) and graphene (Gr) nanoparticles across varying masses from 5 to 200 mg/l. The results show that the LCV increases with the addition of nanoparticles, with the most significant enhancement observed in diesel mixed with graphene, particularly at higher nanoparticle masses. Diesel mixed with aluminum oxide and copper oxide also demonstrates improved LCV compared to pure diesel, though to a lesser extent than the graphene mixture. This suggests that incorporating nanoparticles, especially graphene, into diesel fuel could potentially enhance its energy efficiency (4, 5).

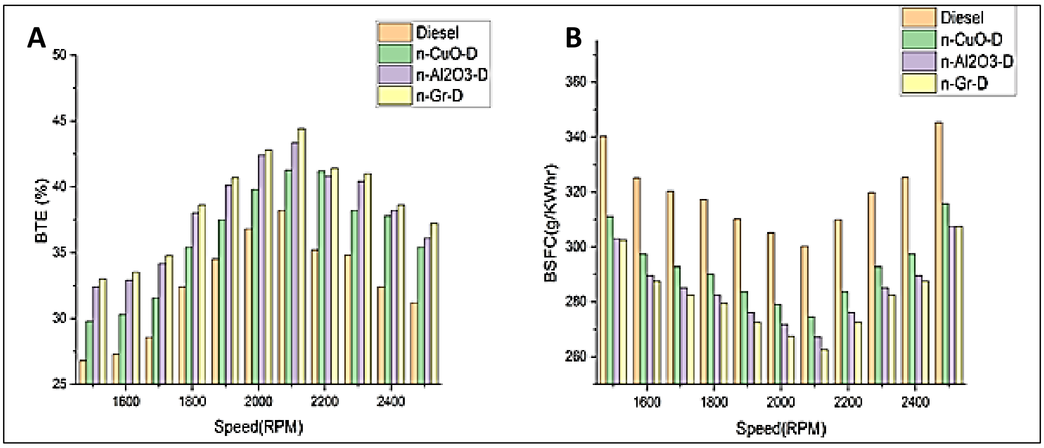

Figure 8: Effect of Speed on: **A**. Engine BTE, **B.** Engine BSFC

In this investigation, Figures 8A and 8B, assessed the impact of conventional diesel and various metal oxide-based nanoparticles on engine performance specifically focusing on Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE). The results indicate that incorporating nanoparticles into diesel fuel leads to a notable reduction in BSFC, reflecting improved fuel efficiency. Gr-based nanodiesel demonstrated the lowest BSFC due to its superior heating value, resulting in reductions of up to 12.5% compared to conventional diesel. Al_2O_3 and CuO nanoparticles also contributed to reductions in BSFC with decreases of up to 10.9% and 8.5%, respectively. In contrast neat diesel fuel showed the highest BSFC due to its lower heating value. Additionally, as engine speed increased BSFC rises across all fuel types due to the higher fuel injection demands required to maintain the increased speed. The high catalytic activity of metal oxide nanoparticles enhanced fuel economy by promoting better combustion efficiency, reducing ignition delay and improving air/fuel mixing, leading to more efficient stoichiometric combustion. The experimental data is robustly validated by reference (16-18) that support these findings.

Regarding Brake Thermal Efficiency (BTE) the addition of nanoparticles also resulted in significant improvements. BTE which measures the efficiency of converting fuel energy into mechanical work increased with the addition of nanoparticles, despite a general decrease at higher engine speeds due to insufficient air leading to uneven combustion. The largest BTE improvements were observed with Gr based nanodiesel showing increases of up to 16.2%. Al_2O_3 and CuO nanoparticles also led to BTE enhancements, with increases of up to 13.5% and 8% respectively as shown in figure 8B. These improvements in BTE across all fuel types underscore the benefits of nanoparticle inclusion in enhancing thermal efficiency. Overall the study demonstrates that metal oxide nanoparticles especially graphene can significantly improve both BSFC and BTE leading to better overall engine performance. The experimental data is robustly validated by reference (16-18) that support these findings.

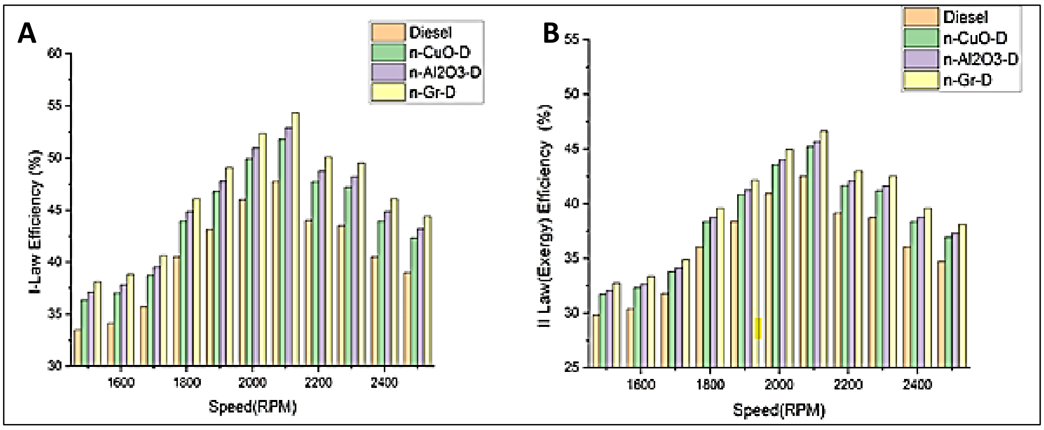

Figure 9: Effect of Speed on: **A.** Engine I-Law Efficiency, **B.** Engine II-Law (Exergy) Efficiency

The efficiency of a heat engine influenced by the first and second laws of thermodynamics varies with changes in engine speed. According to the first law which relates efficiency to the ratio of useful work output to heat input efficiency can improve as engine speed increases if the work output rises while heat input remains constant. However if more heat is required to maintain higher speeds efficiency may either stay constant or slightly decrease. Incorporating metal oxide nanoparticles such as CuO, Al_2O_3 and Gr into diesel fuel significantly enhances first law efficiency compared to conventional diesel. The first law efficiency increases by approximately 4.2% to 13.8% with the highest improvements observed when grapheme-based nanodiesel is used. These enhancements are consistent across different engine conditions indicating the positive impact of nanoparticles on fuel efficiency as shown in Figure 9A. The experimental data is robustly validated by previous research that supports these findings (19).

The second law of thermodynamics, which accounts for entropy and the generation of waste heat, also shows improvement with the addition of nanoparticles although this efficiency can be more complex due to the effects of entropy at higher engine speeds. Despite these complexities second law efficiency improves by 2.9% to 9.8% with the inclusion of CuO, Al_2O_3 and Gr-based nanodiesel demonstrating better energy utilization. The study concludes that adding metal oxide nanoparticles especially grapheme to diesel fuel significantly boosts both first and second law efficiencies. These enhancements lead to improved engine performance across various operating conditions, making nanoparticle-infused diesel a promising option for more efficient energy conversion in engines as shown in Figure 9B. The experimental data is robustly validated by reference (19) that supports these findings.

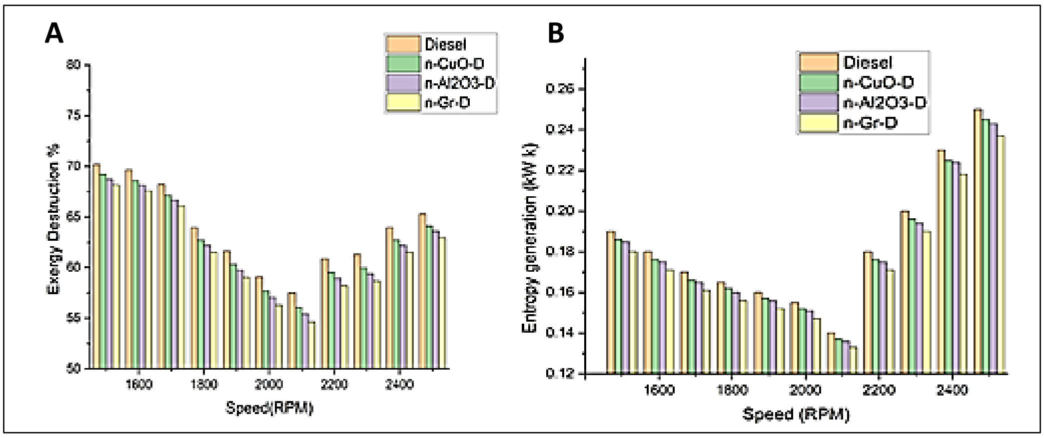

Figure 10: Effect of Speed on: **A.** Entropy Generation, **B.** Exergy Destruction

Entropy generation in a heat engine is a measure of inefficiencies and irreversibility during the conversion of heat into work. Two key factors influencing entropy generation are engine speed and fuel calorific value. Generally higher engine speeds lead to increased mechanical stresses, friction, and faster thermodynamic processes, all of which amplify entropy generation due to greater irreversibility. Conversely fuels with higher calorific values can mitigate entropy generation by providing more energy for work conversion, though they do not eliminate it entirely due to unavoidable inefficiencies like friction, heat transfer losses, and imperfect thermodynamic processes. Therefore optimizing both engine design and fuel selection is essential to reduce entropy generation and enhance overall efficiency.

When comparing the impact of different nanoparticle-infused fuels on entropy generation, it is observed that the introduction of CuO, Al_2O_3 and Gr-based nanodiesel results in significant reductions in entropy generation compared to conventional diesel. Specifically, entropy generation decreases by approximately 1.8% to 6.5%, depending on the nanoparticle and the operating conditions, with the most substantial reduction occurring with grapheme-based nanodiesel. This trend highlights the effectiveness of nanoparticle additives in improving the thermodynamic efficiency of the engine by reducing entropy generation as shown in Figure 10A. The experimental data is robustly validated by reference (20-22) that support these findings.

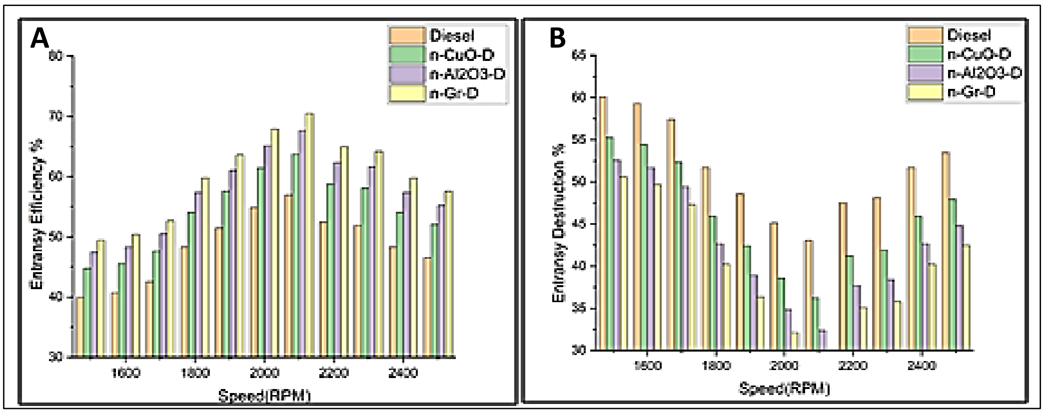

Figure 11: Effect of Speed on: **A.** Entransy Efficiency, **B.** Entransy Destruction

The study highlights the impact of nanoparticle-enhanced fuels on improving entransy efficiency in heat engines. Entransy efficiency which accounts for both the quantity and quality of energy conversion shows significant improvements with the use of metal oxide and graphene-based nanoparticles in diesel fuel. Across various test fuels, entransy efficiency increases by up to 21% with the addition of Gr-based nanodiesel followed by 18% and 16% improvements for Al_2O_3 and CuO-based nanodiesel, respectively, compared to conventional diesel fuel. The data shows that the highest improvements in entransy efficiency are achieved with graphene-based nanodiesel as shown in Figure 11A. The experimental data is robustly validated by reference (20-22) that support these findings.

Additionally, entransy destruction, which represents the irreversible loss of energy during the conversion process, decreases significantly with nanoparticle incorporation. The use of nanoparticles reduces energy losses by up to 6.5%, leading to more efficient energy conversion. However, as engine speed increases, entransy destruction begins to rise due to increased irreversibility's such as friction and heat dissipation. Overall, the findings suggest that optimizing engine design and fuel formulations with nanoparticles can effectively reduce energy losses and enhance overall efficiency in heat engines, as shown in Figure 11B. The experimental data is robustly validated by reference (20-22) which support these findings.

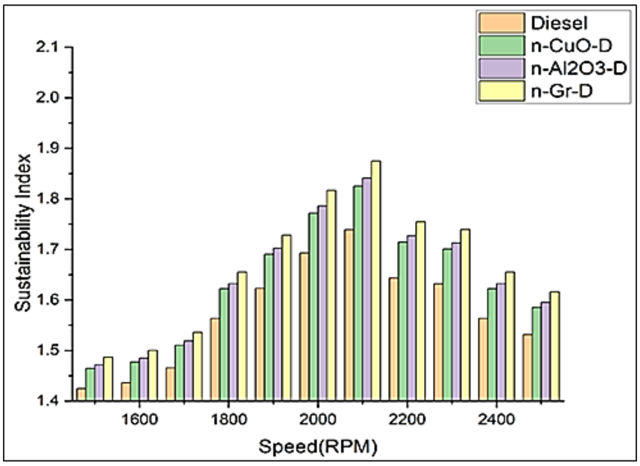

Figure 12: Effect of Speed on Sustainability Index of Engine Performance

The sustainability index of a heat engine assesses the environmental, economic and social sustainability of a fuel based on the engine's running speed. This index considers multiple sustainability related variables. Speed can impact the environmental effects of the tested fuel engine by influencing emissions and fuel consumption. Increased speeds can result in higher emissions of pollutants and greater fuel usage, which can affect air quality and contribute to climate change. The engine speed can impact the economic sustainability of fuel by influencing fuel efficiency and operational expenses. Optimizing engine speeds can increase fuel efficiency and lower operational costs, thus improving the economic feasibility of the fuel. Social Implications: Speed affects noise levels, safety and community acceptance. Elevated engine speeds can lead to higher levels of noise pollution and safety issues, which could impact the societal approval of the fuel. The sustainability index offers a comprehensive evaluation of a fuel sustainability performance in a heat engine by examining its relationship with engine speed and sustainability features. Stakeholders can use this information to make well informed decisions about adopting and implementing the fuel, considering its environmental, economic and social impacts at various engine speeds as shown in to Figure 12.

Conclusion

The effects of addition of CuO, Al_2O_3 and Gr nanoparticles with surfactant to pure diesel fuel are investigated on the energy, exergy and entransy balance of a diesel engine in this study. Nanoparticle and surfactant mass range from 5 to 200 mg and 100 to 300 mg per liter of diesel fuel. The effects of sonication time and mass concentration on heat transport were studied. This study found that nanodiesel has better thermal properties than pure diesel. The results for the tested fuels are compared with each other. Since different techniques produce varied results, more experimental research is needed to determine the best nanofluid production method. Accordingly, the following main conclusions are derived.

- When compared quantitatively with pure diesel in terms of lower calorific value of diesel-Al_2O_3, diesel-CuO and diesel-Gr based nanodiesel at mass fractions of 5 to 200 mg/l average increase by 6.2%, 6.92% and 11.5% correspondingly.

- When compared to pure diesel, diesel-Al_2O_3, diesel-CuO and diesel-Gr based nanodiesel with displayed maximum thermal conductivity enhancements of 16.2%, 25% and 29.5% at different mass fractions. The higher heat transmission capabilities of the nanodiesel mixes are highlighted by these technological advancements in thermal conductivity.
- According to experimental findings, when pure diesel is compared to diesel-Al_2O_3, diesel-CuO and diesel-Gr based nanodiesel the maximum BTE was found to be 8%, 13%, 16%, depending on nano-catalyst blend, while the highest BSFC drops was found to be 8.5%, 10.9% and 12.5% for CuO, Al_2O_3 and Gr based nanodiesel test fuel respectively.
- The highest increase in exergy efficiency was found to be 6.4%, 7.5% and 9.8% while entransy efficiency increased by 13%, 18% and 21% for CuO, Al_2O_3 and Gr based nanodiesel test fuel respectively. In comparison with diesel fuel the highest drop in exergy destruction was found to be 5%, 6.3% and 7.5% while entransy efficiency decreased by 9.4%, 11.5% and 16.3 % for CuO, Al_2O_3 and Gr based nanodiesel test fuel respectively. Their findings showed that nanodiesel fuel worked better at high engine speeds but that conventional diesel fuel performed better at low engine speeds.

This present study is focused on examining the effects of CuO, Al_2O_3 and Gr nanoparticle and surfactant addition into pure diesel on the energy and exergy balance of a diesel engine. In future further study is recommended to investigate the optimum percentages of nanoparticles and surfactant that should be added to improve and optimize the exergy and energy efficiencies.

Abbreviations

Al_2O_3: Aluminium Oxide, BSFC: Brake Specific Fuel Consumption, BTE: Brake Thermal Efficiency, CuO: copper oxide, Gr: Graphene, HTC: Heat Transfer Coefficient, MNP: Mass of Nanoparticle, MSP: Mass of Surfactant, SDS: Sodium Dodecyl Sulphate, ST: Sonication Time.

Acknowledgement

Heartfelt thanks to Medicaps University, Indore, for providing adequate facilities in carrying out this study.

Author Contributions

Each of the mentioned authors has approved the work and contributed significantly, directly, and intellectually.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Declaration of Artificial Intelligence (AI) Assistance

Generative AI tools were used only for language editing. All research ideas, analyses and conclusions are solely those of the authors.

Ethics Approval

Not Applicable.

Funding

The authors did not receive funding support from any organization for the submitted work.

References

1. Doğan B, Erol D. The investigation of energy and exergy analyses in compression ignition engines using diesel/biodiesel fuel blends-a review. Journal of Thermal Analysis & Calorimetry. 2023;148(5):1765-82.
2. Şanli BG, Uludamar EJES, Part A: Recovery, Utilization, Effects E. Energy and exergy analysis of a diesel engine fuelled with diesel and biodiesel fuels at various engine speeds. 2020;42(11):1299-313. https://doi.org/10.1080/15567036.2019.1635229
3. Yılmaz Aydın D, Gürü M. Nanofluids: Preparation, stability, properties, and thermal performance in terms of thermo-hydraulic, thermodynamics and thermo-economic analysis. Journal of Thermal Analysis and Calorimetry. 2022;147(14):7631-64.
4. Patel P, Pathak R. Experimental analysis and comparison of thermophysical properties of the three different hybrid nano-catalyst blended diesel fuels. Australian Journal of Mechanical Engineering. 2025;23(3):628-43.
5. Patel P, Pathak R, Shukla AK. Experimental analysis of thermophysical properties of the nano-catalyst blended diesel fuel. In: International Conference on Scientific and Technological Advances in Materials for Energy Storage and Conversions. Singapore: Springer Nature Singapore. 2023; 109-126. https://ouci.dntb.gov.ua/en/works/7pgYY5r9/
6. Sajid MU, Ali HM. Thermal conductivity of hybrid nanofluids: a critical review. International Journal of Heat and Mass Transfer. 2018;126:211-34.
7. Kazemi I, Sefid M, Afrand M. Improving the thermal conductivity of water by adding mono & hybrid nano-additives containing graphene and silica: A comparative experimental study. International Communications in Heat and Mass Transfer. 2020;116:104648.

https://www.sciencedirect.com/journal/international-communications-in-heat-and-mass-transfer

8. Xian HW, Sidik NA, Saidur R. Impact of different surfactants and ultrasonication time on the stability and thermophysical properties of hybrid nanofluids. International Communications in Heat and Mass Transfer. 2020;110:104389.
9. Sujith SV, Kim H, Lee J. A review on thermophysical property assessment of metal oxide-based nanofluids: industrial perspectives. Metals. 2022;12(1):165. https://www.mdpi.com/2075-4701/12/1/165
10. Xian HW, Sidik NAC, Aid SR, *et al*. Review on preparation techniques, properties and performance of hybrid nanofluid in recent engineering applications. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences. 2018;45(1):1-13.
11. Kanti P, Sharma K, Jamei M, Kumar HP. Thermal performance of hybrid fly ash and copper nanofluid in various mixture ratios: experimental investigation and application of a modern ensemble machine learning approach. International Communications in Heat and Mass Transfer. 2021;129:105731. https://www.semanticscholar.org/paper/408f59bad37ea124e333468596304e882942cdf3
12. Mercan H, Çelen A, Taner T. Thermophysical and rheological properties of unitary and hybrid nanofluids. Advances in Nanofluid Heat Transfer: Elsevier; 2022. p.95-129. https://doi.org/10.1016/B978-0-323-88656-7.00005-2
13. Yildiz I, Caliskan H, Mori K. Exergy analysis and nanoparticle assessment of cooking oil biodiesel and standard diesel fueled internal combustion engine. Energy & Environment. 2020;31(8):1303-17.
14. Xiao H. Derivation of generalized thermoelectric energy equations and the study of thermoelectric irreversible processes based on energy, exergy, and entransy analysis. Energy Science & Engineering. 2024;12(1):39-51.
15. Shadidi B, Alizade HHA, Najafi G. Performance and exergy analysis of a diesel engine run on petrodiesel and biodiesel blends containing mixed CeO2 and MoO3 nanocatalyst. Bbiofuels. 2022;13(1):1-7.
16. Venkatesan SP, Kadiresh PN, Beemkumar N, *et al*. Combustion, performances, and emissions characteristics of diesel engine fuelled with diesel-aqueous zinc oxide nanofluid blends. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2023;45(1):2922-36.
17. Rastogi P, Kumar N, Sharma A, *et al*. Sustainability of aluminium oxide nanoparticles blended mahua biodiesel to the direct injection diesel engine performance and emission analysis. Pollution. 2020;6(1):25-33.
18. Nie X, Bi Y, Liu S, Shen L, *et al*. Impacts of different exhaust thermal management methods on diesel engine and SCR performance at different altitude levels. Fuel. 2022;324:124747. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4048807
19. Karami S, Gharehghani A. Effect of nano-particles concentrations on the energy and exergy efficiency improvement of indirect-injection diesel engine. Energy Reports. 2021;7:3273-85.
20. Upadhya SM, Raju SSR, Raju C, *et al*. Importance of entropy generation on Casson, Micropolar and Hybrid magneto-nanofluids in a suspension of cross diffusion. Chinese Journal of Physics. 2022;77:1080-101.
21. Sayin Kul B, Kahraman A. Energy and exergy analyses of a diesel engine fuelled with biodiesel-diesel blends containing 5% bioethanol. Entropy. 2016;18(11):387. https://ui.adsabs.harvard.edu/abs/2016Entrp..18..387S/abstract
22. Lone SA, Al-Essa LA, Al-Bossly A, *et al*. Entropy minimization of GO–Ag/KO cross-hybrid nanofluid over a convectively heated surface. Nnaotechnology Reviews. 2023;12(1):20230101. https://psau.sa.elsevierpure.com/en/publications/entropy-minimization-of-go-agko-cross-hybrid-nanofluid-over-a-con

How to Cite: Patel P, Shrotriya A, Patel G. Nano Catalyst Impact on Exergy Analysis of CI Engine with Diesel–CuO, Gr and Al_2O_3 Blends. Int Res J Multidiscip Scope. 2025; 6(4):1351-1361.
doi: 10.47857/irjms.2025.v06i04.07236