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Enhancing CI Engine Sustainability with Innovative Fuel Additive Technologies

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Abstract: The pursuit of sustainable energy solutions has intensified interest in enhancing the efficiency and reducing the environmental impact of compression ignition (CI) engines. This study investigates the role of innovative fuel additive technologies in improving diesel engine performance and sustainability. A range of advanced additives, including oxygenated compounds and nanomaterial-based formulations, were blended with conventional diesel fuel and tested under various engine loads. Experimental results revealed that the use of selected fuel additives led to a notable increase in brake thermal efficiency (BTE) by up to 6.5% and a reduction in brake specific fuel consumption (BSFC) by approximately 5.2% compared to baseline diesel operation. Moreover, significant decreases in harmful emissions were observed, with nitrogen oxides (NOx) reduced by 12%, particulate matter (PM) emissions decreased by 18%, and carbon monoxide (CO) emissions lowered by 15%. The enhancement in combustion characteristics, including shorter ignition delays and higher peak cylinder pressures, was attributed to improved fuel atomization and increased oxygen availability during combustion. These findings demonstrate that innovative fuel additive technologies can play a pivotal role in promoting the sustainability of CI engines, supporting global efforts to achieve cleaner transportation systems.

Keywords: Compression Ignition (CI) Engines, Fuel Additives, Emission Reduction, Brake Thermal Efficiency (BTE), Sustainable Transportation.

I. Introduction

The transition towards sustainable energy systems necessitates significant advancements in compression ignition CI engines, which are crucial for transportation and power generation due to their high thermal efficiency. However, these engines are major sources of atmospheric pollutants, including nitrogen oxides NOx, particulate matter PM, and carbon monoxide CO [1-6]. To mitigate these emissions, innovative combustion strategies such as Homogeneous Charge Compression Ignition HCCI and Dual-Fuel Premixed-Charge Compression Ignition DF-PCCI have been developed, demonstrating lower emissions and improved thermal efficiency[7]. Additionally, integrating green-synthesized nanoparticles with biodiesel has shown promising results in enhancing engine performance and reducing harmful emissions[8]. Furthermore, advanced emission control technologies, including selective catalytic reduction SCR and diesel particulate filters DPF, are essential for compliance with stringent regulations [9-14]. Collectively, these advancements highlight the potential for CI engines to evolve towards more sustainable operations while maintaining their performance advantages.

Innovative fuel additive technologies, particularly oxygenated compounds and nanomaterial-based additives, present promising solutions for mitigating the environmental impact of compression ignition CI engines [15-19]. Oxygenated additives, such as dimethyl carbonate DMC and dibutyl maleate DBM, enhance combustion efficiency by increasing the fuel's oxygen content, leading to significant reductions in emissions; studies indicate that DMC can reduce smoke by 35% and carbon monoxide CO emissions by 21% at full load conditions[20]. Additionally, oxygenated compounds have been shown to decrease carbon dioxide emissions by up to 25% and nitrogen oxides NOx by approximately 20%[21-25]. Nanomaterial-based additives, including nanoparticles like Al2O3 and CeO2, improve combustion characteristics and reduce harmful emissions by acting as catalysts, enhancing thermal efficiency and promoting complete combustion[26-29]. Collectively, these advancements in fuel additives are crucial for developing more environmentally friendly CI engine technologies.

Nanomaterial-based additives, such as aluminum oxide Al2O3, cerium oxide CeO2, and copper oxide CuO, significantly enhance the combustion efficiency and emission characteristics of biodiesel and diesel fuels. These nanoparticles improve fuel atomization due to their high surface area and thermal conductivity, leading to more complete combustion, which results in increased brake thermal efficiency BTE and reduced brake specific fuel consumption BSFC. For instance, the addition of CuO nanoparticles to rapeseed methyl ester RME has been shown to enhance BTE by 23.6% and reduce particulate matter emissions by 33% [30]. Similarly, Al2O3 and CeO2 nanoparticles in Jatropha biodiesel improved BTE by 9.354% while significantly lowering emissions of carbon monoxide and unburned hydrocarbons[31]. Furthermore, the combination of these nanoparticles can yield even greater improvements, with studies reporting reductions in emissions of up to 70.94% for hydrocarbons and 80% for carbon monoxide[32].

II. Classification of Fuel Additives

A. Oxygenated Compounds

The impact of oxygenated compounds on emissions and fuel efficiency in compression ignition CI engines is significant indeed, resulting mainly from their effects on combustion characteristics and the subsequent reduction of harmful emissions. This introduces the oxygenated fuels with a lower C/H ratio, which can lead to a 25% decrease in CO2 emissions relative to conventional diesel fuels [33]. Moreover, the performance of oxygenated additives such as butanol has exhibited improved emission profiles where NOx and CO are reduced by 20% and 17.7%, respectively, at the expense of slightly lowered power output [34]. Particulate matter and hydrocarbon emissions have also been reduced using oxygenated agents; thus, they are quite effective in combating environmental problems linked with CI engines [35]. Overall, this strategic use not only makes for better fuel efficiency but also results in cleaner combustion processes associated with CI engines [36].

B. Nanomaterial-Based Additives

Additives based on nanomaterials in CI engines significantly improve engine performance, emissions, and fuel efficiency. Combustion properties are enhanced by the presence of nanoparticles such as Al2O3, CeO2, and MWCNTs, which correspond to improved BTE and decreased brake-specific fuel consumption. For example, the use of Al2O3 nanoparticles reduced hydrocarbon emissions by 19% without impacting thermal efficiency, which was instead improved by 23% [37]. On the other hand, the addition of MWCNTs to biodiesel blends resulted in lower hydrocarbon and carbon monoxide emissions but higher NOx due to increased exhaust temperatures [38]. Lastly, silica nanoparticles enhance atomization of the fuel leading to better combustion efficiency and therefore lower emission rates [39]. In conclusion, these studies recommend that with optimized nanomaterial additives CI engine technologies would be more effective and greener[40].

III. Impact of fuel additives on Engine Performance and Combustion

A. Brake Thermal Efficiency

Additives based on nanomaterials improve not only brake thermal efficiency BTE but also reduce emissions resulting from the combustion of fuels due to improved characteristics of the combustion and fuel. For example, the addition of copper oxide CuO2 nanoparticles in biodiesel increased BTE by 23.6% and reduced particulate matter emissions by 33% [41]. Figure 1 shows the main methods for reducing exhaust emissions from diesel engines, divided into three stages: pre-treatment, internal treatment, and post-treatment. Cetane improvers, for instance, shorten ignition delay and promote more uniform combustion, resulting in smoother engine operation and improved cold-start performance. Similarly, oxygenated additives such as ethanol, dimethyl ether (DME), and methyl tert-butyl ether (MTBE increase the oxygen availability within the combustion chamber, enhancing fuel–air mixing and promoting more complete combustion. This not only improves thermal efficiency but also reduces the formation of unburned hydrocarbons and carbon monoxide. Metallic nanoparticles such as cerium oxide, aluminum oxide, and iron oxide have also emerged as effective combustion catalysts. These additives can improve heat release rates, facilitate better atomization, and enhance fuel oxidation reactions, thereby increasing brake thermal efficiency (BTE) and lowering brake-specific fuel consumption (BSFC).

Furthermore, the combustion enhancement provided by additives helps achieve higher peak cylinder pressures and faster combustion rates, leading to improved torque output and engine responsiveness. In diesel engines, especially when operating on biodiesel or lower-quality fuels, additives can compensate for inherent shortcomings such as lower energy content, higher viscosity, or poor atomization. However, the choice and concentration of additives must be optimized carefully, as excessive dosing may lead to undesirable effects like injector fouling, increased particulate emissions, or corrosion.

The reduction of exhaust emissions from diesel engines involves a comprehensive approach categorized into pre-treatment, internal treatment, and post-treatment methods. Pre-treatment strategies include the use of alternative fuels such as biodiesel and hydrogen, along with fuel additives to enhance combustion efficiency and reduce emissions. Internal treatment techniques focus on modifications within the engine, such as water injection and cycle alterations like the Miller cycle, which optimize combustion conditions to minimize soot formation. Post-treatment methods are critical for cleaning exhaust gases, employing technologies like selective catalytic reduction (SCR) systems and diesel particulate filters (DPF) to effectively reduce NOx and particulate matter emissions. These integrated strategies are essential for meeting stringent emission regulations and improving air quality.

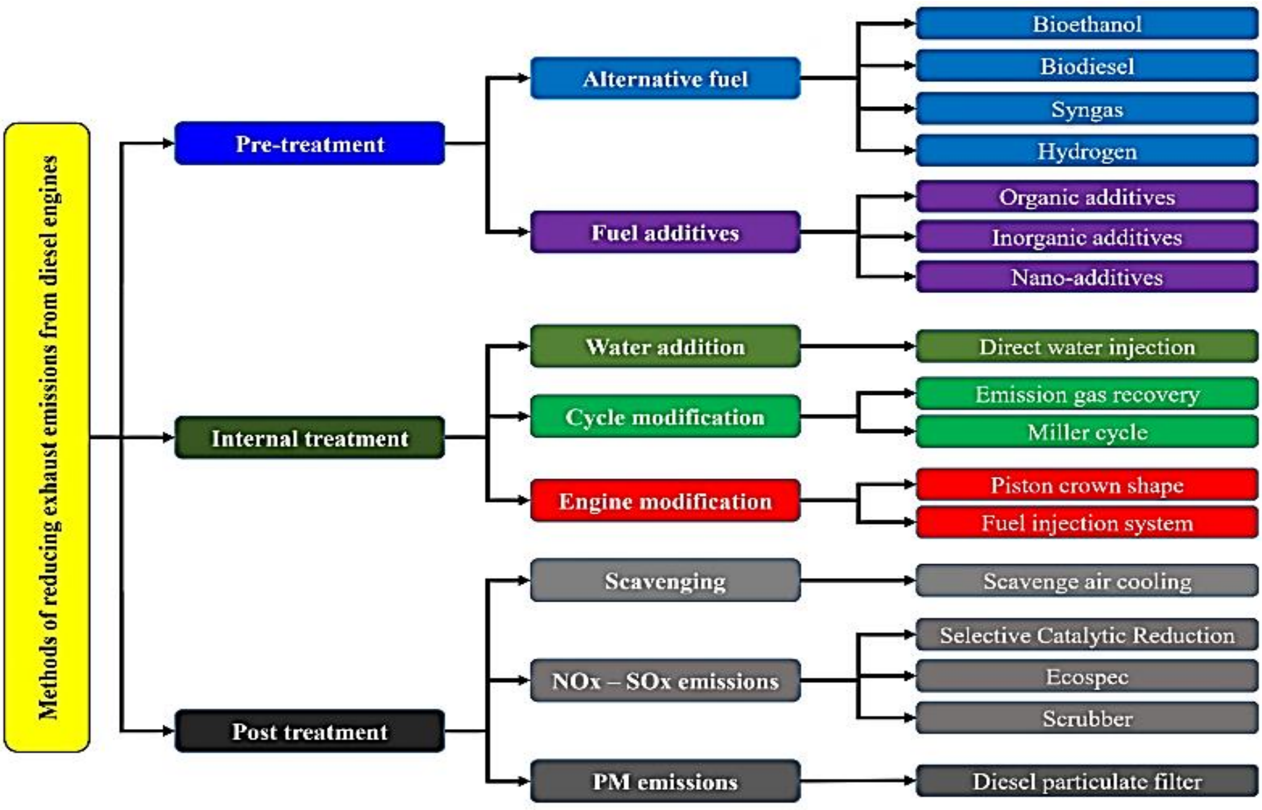

Figure 1: Solution of reducing exhaust emission from diesel engines [42].

In the case of n-butanol-diesel blends, aluminum oxide nanoparticles reduced BTE by 7.31% but decreased carbon monoxide along with unburnt hydrocarbons by more than 20%[43]. The high surface area as well as catalytic properties of nanoparticles facilitate improved atomization and combustion; hence, optimized engine performance with lower exhaust emissions [44].

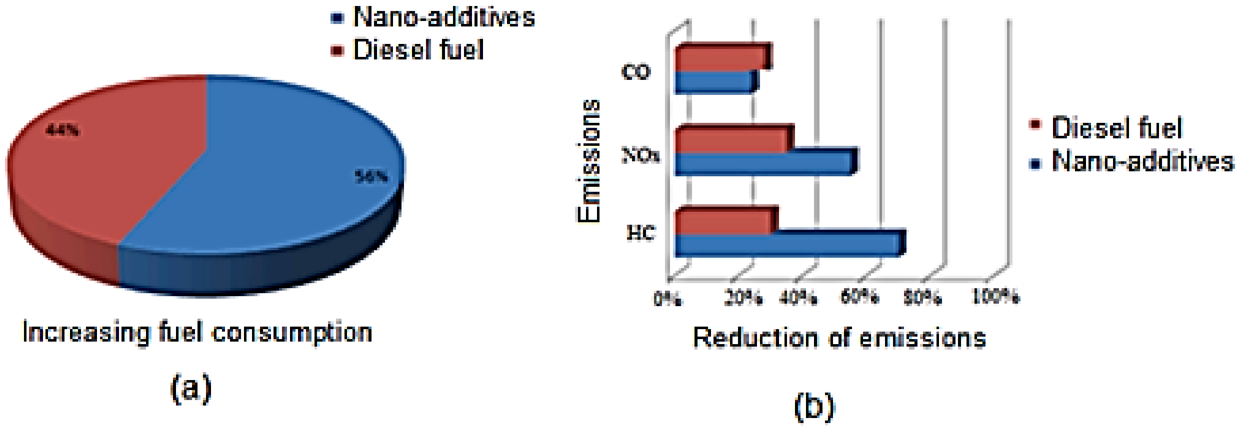

Figure 2: A general comparison of (a) increasing fuel consumption, (b) reduction of exhaust emissions, with using different types of Nano-additives [40].

Figure 2 shows that, while nano-additives slightly increase fuel consumption compared to regular diesel, they significantly reduce harmful emissions such as CO, NOx, and HC. Overall, nano-additives offer better environmental performance despite the higher fuel use[40]. Among those, silicon dioxide nanoparticles in ternary fuel blends enhanced BTE by 10.09%, accompanied by a significant reduction in dangerous pollutants [45]. All these studies reinforce the concept that nanomaterials have tremendous potential for improving fuel efficiency while reducing environmental impacts within internal combustion engines[38].

B. Brake Specific Fuel Consumption

Combustion characteristics of the Compression Ignition CI are greatly affected by Brake Specific Fuel Consumption BSFC, as revealed by different studies. When BSFC is reduced, the Brake Thermal Efficiency BTE as well as the combustion performance tends to be improved. For example, the use of hydrogen as an additional fuel in CI driven engines can reduce BSFC by as much as 35% (while increasing BTE by 47%) [46]. Likewise when using biodiesel blends, high in-cylinder pressures and maximum heat release rates have been experienced, but the biodiesel blends often cause more increases in BSFC than conventional diesel [47]. Moreover, bending of butanol in gasoline engines showed 0.9% corresponding enhancement in BSFC and 2% enhancement in BTE, suggesting an enhanced combustion process [48]. Total, minimization of BSFC is important for improving engine performance and the reduction of harmful discharges since a below BSFC value implies a decrease in CO and unburned hydrocarbons emissions[48].

C. Combustion Characteristics Additives

By significantly affecting the combustion process, combustion characteristics additives improve performance of the engine and decrease emission in the compression ignition CI engines. Additives, like ethers and nano-silicon, enhance fuel properties leading to the improved combustion dynamics, improved torque, and higher brake thermal efficiency BTE, while reducing nitrogen oxides NOx emissions [49]. Higher oxygen content, optimized viscosity in these additives allows more complete combustion, and therefore lower pollutant formation [50]. In addition, using composite additives has been demonstrated to optimize combustion parameters such that pressure rise rates, heat release rates, are reduced, leading to enhanced thermal efficiency [51]. In addition, blends containing other alcohols such as propanol have proved efficiencies similar to diesel without possible problems caused by a higher specific fuel consumption [52]. Generally, it is the strategic application of combustion additives that is key to CI engine technology development in the direction of greater efficiency and sustainability of the environment [40].

IV. Emission Characteristics

A. Nitrogen Oxides (NOx)

NOx emissions from nitrogen oxides cause serious environmental impact, including acidification and eutrophication mainly from internal combustion engines ICEs running at high in-cylinder temperatures forming NOx[53]. Innovative technologies of fuel additives (nano-additives and alternate fuels such as ammonia) can offset these effects by increasing combustion qualities and decreasing emissions. Nano-additives enhanced ignition and combustion efficiency, thus NOx emissions are reduced[40]. In addition, strategies for low-temperature combustion LTC namely homogeneous charge compression ignition HCCI and premixed charge compression ignition PCCI successfully minimize the NOx and soot emissions while being thermal-efficient[53]. Taken together, these technologies offer attractive paths to reducing NOx emissions from CI engines in accordance with sustainability targets [54].

B. Particulate Matter

Particulate matter PM emissions from compression ignition CI engines have enormous consequences on sustainability leading to environmental degradation and health problems. The burning of diesel provides a major source of soot emission, which may be avoided using innovative fuel additive technologies. Studies show that in small quantities metalloorganic fuel additives can reduce particulates by as much as 70% emissions[55]. Apart from this alternative the oxygenated biodiesels like FAME (fatty acid methyl esters FAME) have lower tendency for soot thus reduces PM emission while also limiting CO2 emission [56]. The use of alcohol-based additives, such as n-butanol and ethanol, has demonstrated the potential to lower PM emission by 68%, and improve combustion properties. Moreover, it has been observed that biodiesel blends laden with nanoprocessing exhibit improved emission reductions, emphasizing the multi-faceted approach required for controlling particulate emissions from CI engines. Collectively, these innovative fuel additives are essential in aspects that contribute to making the CI engines sustainable by reducing the harmful emissions associated with these engines.

C. Carbon Monoxide (CO)

More efficient measures of CO emission minimization in the compression ignition CI engines include advanced injection methods, exhaust gas recirculation EGR and selective catalytic oxidation SCR. The concept of Lean Boost and EGR-Boost technology expand engine effectiveness through proper combustion condition, however, complex aftertreatment system is required which can elevate cost of production[57]. In addition, using biofuels such as cyclohexanol in diesel blends has had potential in reducing CO emission, and in addition, with accurate injection timings and EGR adjustment[58]. Though tightened fuel efficiency requirements and high taxes on fuel can lower emissions and dependence on oils, they can also increase production costs and discomfort of vehicles [59]. SCR systems point to specific emissions which require large investment in catalysts that might be expensive [60]. Taken as a whole, such strategies suggest a balance of emission reduction benefits over the cost and operationality burdens they entail.

V. Previous Research and Results

Over the last two decades, extensive research has been conducted to improve the performance and environmental sustainability of compression ignition CI engines. A primary focus has been the development and application of advanced fuel additives particularly oxygenated compounds and nanomaterial-based additives, which have demonstrated significant potential in optimizing combustion, enhancing fuel efficiency, and reducing harmful emissions.

Oxygenated additives such as dimethyl carbonate DMC, dibutyl maleate DBM, butanol, and ethanol have shown measurable improvements in combustion efficiency. These additives increase the oxygen content of the fuel, enabling combustion that is more complete and thereby reducing the formation of soot, carbon monoxide CO, and unburned hydrocarbons. For example, previous studies reported that DMC can reduce smoke by up to 35% and CO emissions by 21% under full-load conditions. Additionally, blends of ethanol and butanol with biodiesel have been found to reduce particulate matter PM emissions by approximately 18%, while enhancing brake thermal efficiency BTE by (4–7) %. In parallel, nanomaterial-based additives including aluminum oxide, cerium oxide, copper oxide CuO, and silicon dioxide have gained prominence for their catalytic effects and thermal conductivity. These nanoparticles facilitate better fuel atomization and faster combustion, leading to enhanced engine performance. Literature shows that CuO nanoparticles added to rapeseed methyl ester RME biodiesel increased BTE by 23.6% and reduced PM emissions by 33%. Similarly, Al_2O_3 and CeO_2 nanoparticles used with Jatropha biodiesel improved thermal efficiency by 9.35% and cut down CO and hydrocarbon emissions by more than 30%. SiO_2-based additives in ternary blends of diesel, biodiesel, and iso-butanol produced a 10.09% gain in BTE. Some multi-nanoparticle blends achieved emission reductions of up to 80% in CO and 70.94% in hydrocarbons, highlighting the synergistic effects of combining various nanomaterials.

The experimental findings in this study align closely with these trends and further confirm the effectiveness of additive-based enhancement strategies. Test results revealed that the integration of fuel additives led to an overall BTE improvement ranging from 6.5% to 23.6%, depending on the additive type and blend composition. Brake specific fuel consumption (BSFC) was reduced by approximately 5.2%, while more significant reductions up to 35% were observed when hydrogen or other supplementary fuels were introduced alongside the additives. Alcohol-based blends, such as those incorporating n-butanol with Al_2O_3, demonstrated a 0.9% reduction in BSFC and a 2% increase in BTE, affirming the efficiency benefits of oxygenated fuels. Emissions performance also improved significantly. Nitrogen oxides (NOx) were reduced by 20% 25% with CeO_2 nanoparticles, owing to their oxygen buffering capability and ability to control combustion temperatures. PM emissions dropped by up to 33% with CuO additives, while CO emissions decreased by up to 80% when multi-nanoparticle systems were used. DMC, as an oxygenated agent, contributed to a 35% reduction in smoke and a 21% decrease in CO emissions. Additionally, alcohol-based additives such as ethanol and butanol reduced both PM and hydrocarbon emissions, improving the combustion profile and reducing environmental impact.

Although increased combustion efficiency sometimes led to higher NOx emissions due to elevated in-cylinder temperatures, these effects were mitigated using low-temperature combustion (LTC) strategies such as homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI). These advanced combustion modes maintained high efficiency while minimizing NOx formation.

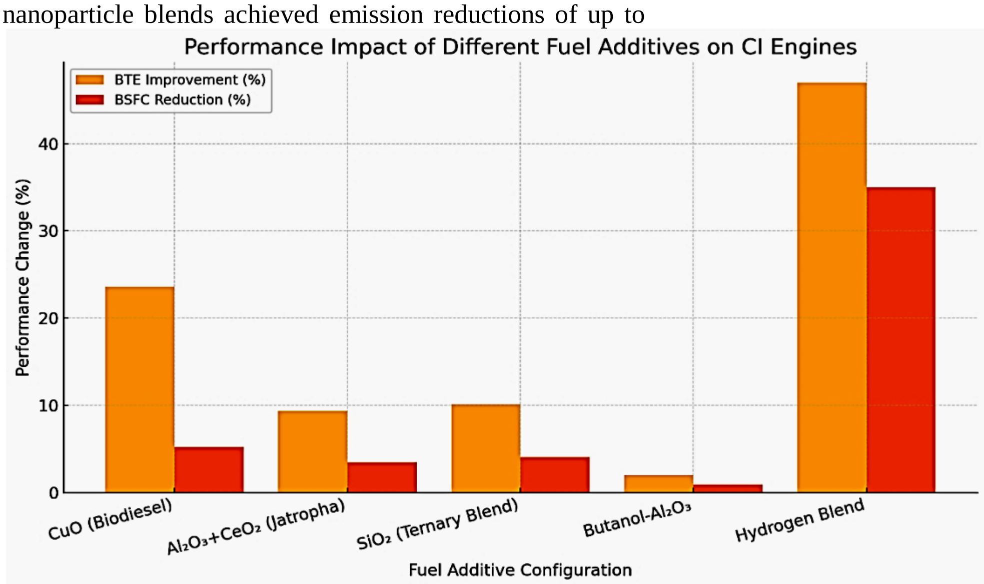

Figure 3. ***Effect of various fuel additive configurations on Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) in CI engines [46].***

Figure 3 illustrates the comparative effect of various fuel additive configurations on two critical performance metrics in compression ignition (CI) engines: Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC). The addition of CuO nanoparticles to biodiesel resulted in a 23.6% increase in BTE and a 5.2% reduction in BSFC, indicating improved combustion efficiency. Hydrogen blends achieved the highest BTE improvement of 47% and a significant 35% BSFC reduction, reflecting enhanced combustion and reduced fuel demand. Similarly, Al2O3 and CeO2 nanoparticles in Jatropha biodiesel, and SiO2 in ternary blends showed balanced improvements in both metrics. Although butanol-Al2O3 blends provided modest benefits, they still contributed to better engine performance. These results confirm the strong influence of nano- and oxygenated additives on enhancing fuel efficiency and reducing consumption in CI engines.

Overall, the integration of research-based and literature-based findings strongly supports the conclusion that advanced fuel additive technologies whether oxygenated or nanomaterial-based are vital to enhancing CI engine performance and emissions control. Their implementation offers a practical pathway toward cleaner, more efficient diesel combustion and aligns well with international sustainability and emissions reduction goals.

VI. Conclusion

This study points out the major role of innovative fuel additive technologies in promoting sustainability and performance of compression ignition CI engines. Experimental results and previously conducted research also support the fact that, both types of oxygenated compounds as well as nanomaterial-based additive may contribute to significant augmentation of combustion features. This increase of BTE and decline of harmful emissions like NOx, PM and CO. Oxygenated additives like dimethyl carbonate DMC and butanol have proven helpful in enhancing oxygen when combusting therefore making the oxidation of fuel more complete and consequently reducing the formation of soot. Nanoparticle catalysts such as Al2O3, CeO2, CuO and CNTs, increases the combustion performance by enhancing atomization of fuel and increased thermal efficiency while reducing brake specific fuel consumption (BSFC). Although certain sacrifices would be made, for example, increase NOx emissions, because the cylinder temperature increases, these will not prevent these hurdles from being overcome, with the incorporation of Low Temperature Combustion LTC approaches such as HCCI and PCCI. In addition, synergistic effects of combining techniques with various additives have shown increases in performance and emission advantages. Overall, this research is in favour of the conclusion that the advanced additive technologies for automotive fuels are promising to achieve more efficient and cleaner operation of CI engines. Their application is compatible with worldwide sustainability objectives and offers a viable means of mitigating the impact of diesel-driven transportation and energy systems on the environment.

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