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Experimental Investigations And CFD Analysis Of Combustion And Emission In CI Engines- A Review

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This work is a review of the analysis of experimental investigations and CFD to understand the combustion and emission characteristics of Compression Ignition (CI) engines. The objective of the review is to synthesize recent studies, analyse of results in CFD and experimental data, and provide recommendations for further research. The focus was made on turbulence and swirl flows, combustion modelling, spray and injection dynamics, and emission formulation in CI engines. It also involved a comprehensive literature review, and critical articles of relevant research articles. The main results suggest the significant impact of CFD simulations focusing on promoting air fuel mixing, combustion efficiency, and emission reduction in CI engines. On the other side, the disparities between the CFD predictions and the experimental data emphasize the need of the on-going work on the modifications of the models. The paper ends with propositions of the outstanding problems and efforts in multi-field approaches and more advanced CFD facilities to solve the issues of CI engines now and in the future.

Keywords Hydrogen; Alternate Fuel; Performance; Emissions; CFD Analysis; CI Engines.

1. Introduction

Compression ignition (CI) engines, commonly referred to as diesel engines, serve a critical function in diverse sectors, including transportation, power generation, and industrial applications. The investigation of combustion and emissions in CI engines is of paramount significance due to their extensive utilization and substantial environmental impact. This research domain focuses on elucidating and enhancing the intricate processes that transpire within the engine cylinder, with the objective of improving performance, fuel efficiency, and mitigating harmful emissions.

The importance of researching combustion and emissions in compression ignition (CI) engines goes beyond environmental considerations. It also tackles crucial aspects such as: Enhancing combustion processes is essential for improving fuel efficiency and decreasing carbon dioxide output, in line with worldwide efforts to combat climate change[1]. Innovative combustion techniques like low-temperature combustion (LTC) and homogeneous charge compression ignition (HCCI) are under investigation to concurrently reduce emissions and increase thermal efficiency[2, 3]. Furthermore, an enhanced comprehension of combustion characteristics facilitates the development of more resilient engines with extended operational lifespans, thereby reducing maintenance expenses and resource utilization [4]. This encompasses research into wear-resistant materials, optimized lubrication systems, and improved combustion chamber designs to minimize thermal and mechanical stresses [5, 6]. Investigation into alternative fuels also supports the transition to sustainable energy through the development of engines capable of operating on renewable and low-carbon fuels, examination of their combustion characteristics, and implementation of necessary engine modifications to accommodate these fuels [7, 8]. These technological advancements have significant economic implications, potentially resulting in reduced fuel consumption, decreased maintenance costs, and increased engine longevity, all of which contribute to enhanced business competitiveness [9]. Moreover, ongoing research assists manufacturers in complying with increasingly stringent emission standards without compromising engine performance, involving innovative technologies to reduce emissions and enhance after treatment systems [10, 11]. The integration of CI engines with electric powertrains in hybrid vehicles presents new opportunities for optimizing combustion and emissions[12], while the development of advanced diagnostics, sensors, and control algorithms enables real-time monitoring and optimization of engine performance[13, 14]. Additionally, noise and vibration reduction research, though not directly related to emissions, plays a vital role in improving overall engine performance and user comfort by addressing combustion-induced noise and vibration[15]. Cold-start emissions remain a key area of focus, with efforts directed at developing rapid warm-up strategies and optimizing fuel injection and combustion for low-temperature conditions [16] [17] Finally, life cycle assessment is becoming increasingly significant in evaluating the environmental impact of CI engines, from production to disposal, guiding the development of more sustainable technologies [18].

2. Combustion Process of CI engines

The combustion process in CI engines involves the injection of fuel into compressed air, resulting in spontaneous ignition. Heterogeneous mixing, high-pressure conditions, and rapid chemical reactions characterize this process. Understanding these phenomena is essential for optimizing engine design, fuel formulation, and control strategies to achieve better performance and reduced emissions [19]. The combustion process in CI engines is a complex interplay of physical and chemical phenomena occurring under extreme conditions. As fuel is injected into the combustion chamber, it encounters highly compressed air at elevated temperatures. This environment triggers a series of events, including fuel atomization, vaporization, and mixing with air. The heterogeneous nature of this mixing process creates localised regions with varying fuel-air ratios, leading to multiple ignition sites and a progressive combustion event. The high-pressure conditions, typically ranging from 30 to 200 bar, further intensify the chemical reactions and influence the combustion dynamics [20]. Figure 1 represents effect on BSFC and $BSNO_x$ emissions at various engine pressures.

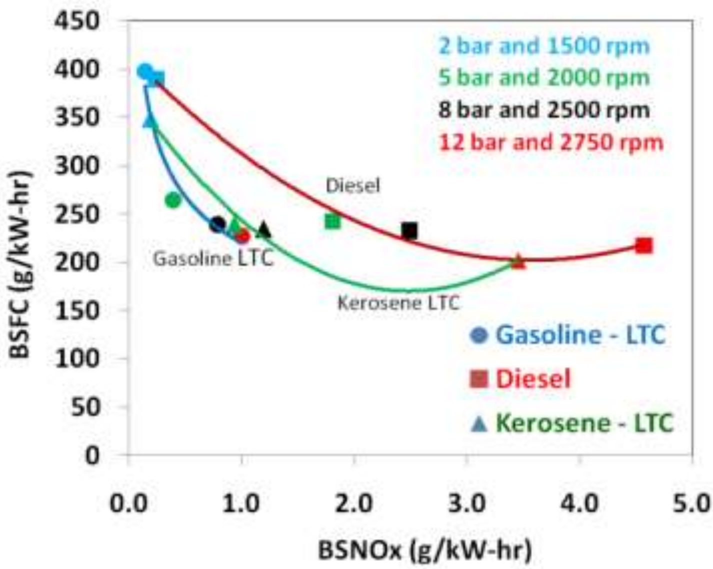

Figure 1: Effect on BSFC and BSNOx emissions [20]

The rapid chemical reactions that follow ignition are characterized by complex kinetics involving hundreds of species and thousands of elementary reactions [21] . These reactions progress through various stages, including low-temperature heat release, negative temperature coefficient (NTC) behavior, and high-temperature heat release. The interplay between these reaction pathways and the turbulent fluid dynamics within the combustion chamber significantly impacts the overall combustion efficiency, power output, and emissions formation. Consequently, a deep understanding of these intricate processes is crucial for engine designers and researchers to develop advanced combustion strategies, such as Low-temperature combustion (LTC) or homogeneous charge compression ignition (HCCI), which aim to simultaneously enhance engine efficiency and mitigate pollutant emissions [22-24] .

3. Emissions from CI engines

Emissions from CI engines, particularly nitrogen oxides (NOx) and particulate matter (PM), have been a major concern due to their adverse effects on human health and the environment. Stringent emission regulations worldwide have driven research efforts to develop innovative technologies and strategies for emission reduction. These include advanced fuel injection systems, exhaust gas recirculation (EGR), aftertreatment devices, and alternative fuels. Compression ignition (CI) engines, while known for their high thermal efficiency and fuel economy, contribute significantly to detrimental emissions, particularly nitrogen oxides (NOx) and particulate matter (PM) [25, 26]. The main reason for higher NOx emissions in diesel engines is the higher excess air ratios, which promote NO formation chemistry [27]. The levels of NOx emissions depend on operating modes that determine high temperatures in the cycle and the excess air coefficient α, which provides free oxygen for nitrogen oxidation [28]. Notably, while biodiesel applications are gaining prominence as an alternative to fossil fuels, biodiesel-fueled CI engines, despite offering improved performance and reduced emissions overall, tend to increase NOx emissions [27, 29]. This presents a challenge in balancing the benefits of alternative fuels with emission control. Furthermore, the utilization of dimethyl ether (DME) as a promising alternative to diesel also encounters the issue of elevated NOx emissions due to high combustion temperatures[30]. Various techniques have been developed to reduce NOx emissions in CI engines. Figure 2 illustrates the Engine-out emissions. These include water injection, emulsification, injection timing retardation, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR) [30]. Water injection and emulsification methods can reduce NOx emissions by 37-60% in biodiesel engines [27]. High EGR rates have shown effectiveness in reducing NOx formation under low-temperature combustion conditions [30]. Advanced technologies like the ALPING engine, which uses natural gas as the primary fuel with a diesel pilot, have demonstrated potential to meet stringent NOx regulations [31]. Furthermore, the addition of ethanol to diesel and biodiesel fuels has shown promise in simultaneously reducing NOx and smoke emissions[32]. As research continues, novel approaches such as using deep neural network models to predict NOx emission reductions in SCR systems are being explored to improve emission control strategies [33].

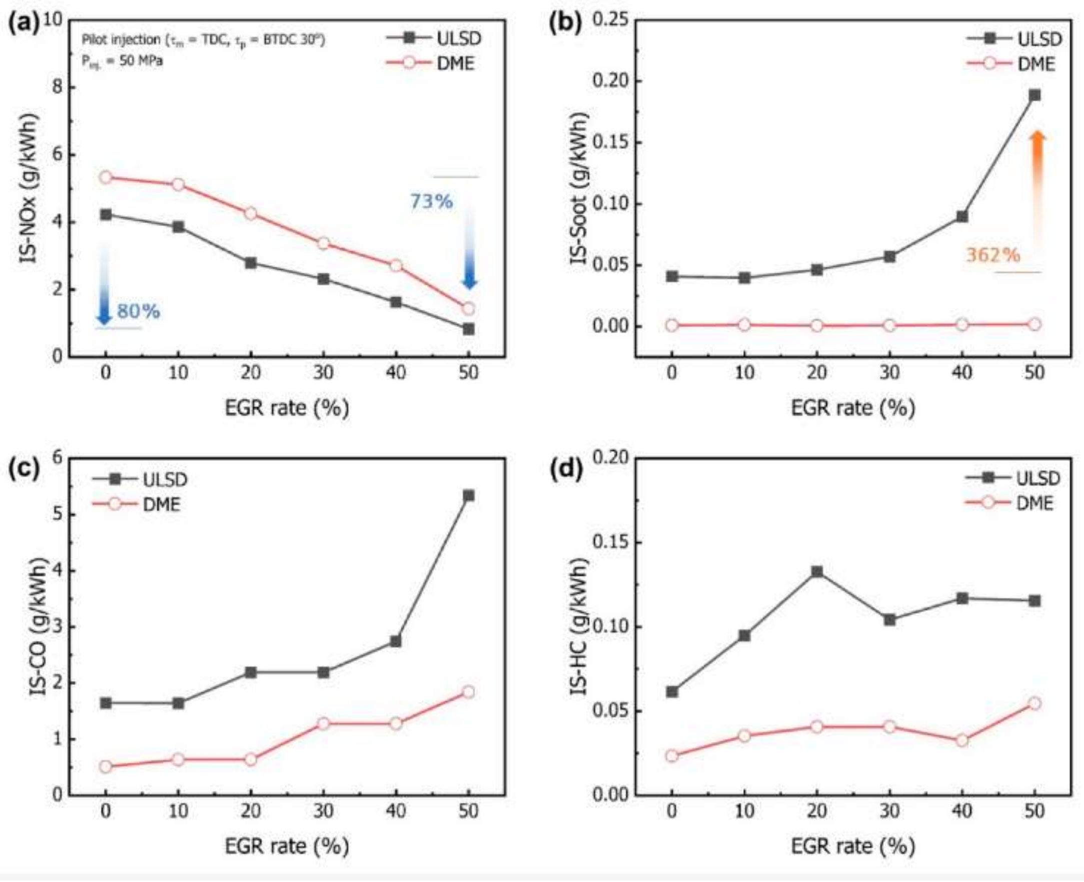

Figure 2 : Engine-out emissions; (**a**) nitrogen oxides, (**b**) soot, (**c**) carbon monoxide and (**d**) hydrocarbon for DME and ULSD fuels as a function of EGR rate[30].

Exhaust gas recirculation (EGR) is a widely adopted technique for reducing NOx emissions in CI engines [34, 35]. By recirculating a portion of the exhaust gases back into the combustion chamber, EGR lowers the peak combustion temperature, thereby suppressing NOx formation. However, the use of EGR can lead to increased PM emissions and reduced engine efficiency, necessitating careful optimization of the EGR rate and other engine parameters[36]. After treatment systems have become an integral part of modern CI engines to meet stringent emission standards. These systems typically include diesel oxidation catalysts (DOC), diesel particulate filters (DPF), and selective catalytic reduction (SCR) systems. DOCs are used to oxidize carbon monoxide (CO) and hydrocarbons (HC), while DPFs trap and oxidize particulate matter[37, 38]. SCR systems employ a urea-based solution to convert NOx into harmless nitrogen and water vapor. The development and optimization of these after treatment technologies continue to be an active area of research, focusing on improving their efficiency, durability, and cost-effectiveness [39, 40]. Figure 3 illustrates NO2/NOX ratio at the engine raw exhaust for all the operating conditions. Alternative fuels and fuel blends have gained significant attention in recent years as a means to reduce emissions and dependence on fossil fuels. Biodiesel, derived from renewable sources such as vegetable oils and animal fats, has shown promise in reducing PM emissions and greenhouse gas emissions. However, its use can lead to increased NOx emissions and potential issues with fuel system compatibility. Other alternative fuels, such as dimethyl ether (DME) and hydrotreated vegetable oil (HVO), are also being investigated for their potential to reduce emissions while maintaining engine performance.

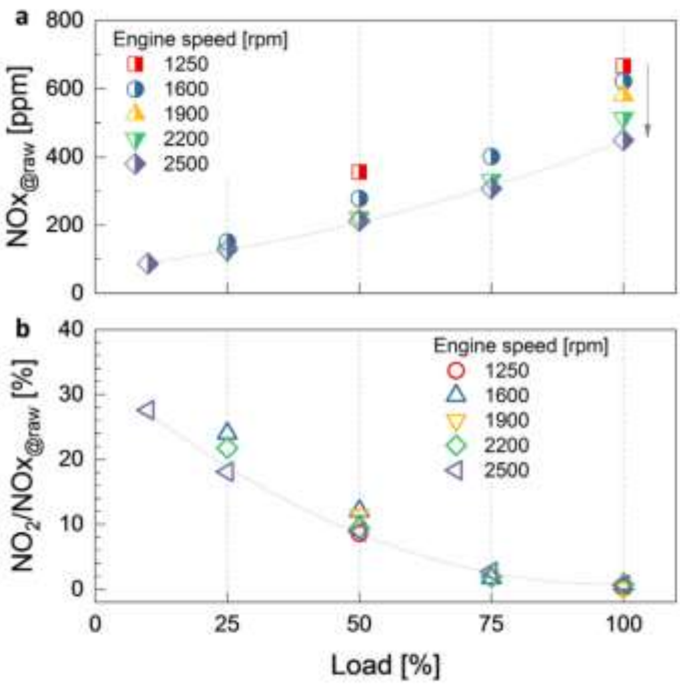

Figure 3. The (a) NOX concentration and (b) the NO2/NOX ratio at the engine raw exhaust for all the operating conditions (The curved fitting through results at the engine speed of 2500 rpm exhibits the trade-off of NOX and NO2/NOX).

Experimental investigations:

Pressure transducers are commonly used to measure in-cylinder pressure, which is crucial for understanding combustion behavior. For example, [41] mentions using large eddy simulations to analyze the pressure field and acoustic emissions in diesel engines. Similarly, [42] discusses measuring in-cylinder pressure to evaluate combustion characteristics in gasoline compression ignition (GCI) engines. Temperature sensors are employed to monitor exhaust gas temperature (EGT), which provides insights into combustion efficiency and emissions formation. Agarwal et al., [42] reports comparing EGT between GCI and conventional diesel combustion (CDC) modes. Agarwal et al., [43] also mentions conducting experiments to observe the effect of exhaust gas recirculation (EGR) on exhaust gas temperatures. Emission analyzers are essential for quantifying various pollutants in the exhaust. Syed and Renganathan [44]discuss measuring NOx and particulate matter (PM) emissions, which are primary concerns in CI engines. Bhave et al., [45] reports measuring NOx emissions in parts per million (ppm) for different operating conditions. Additionally, [43] mentions using opacity measurements to assess particulate emissions. Notably, certain studies employ advanced visualization techniques to obtain more comprehensive insights into combustion processes[42]. Additionally, proper orthogonal decomposition is employed to analyze the modal energy distribution among acoustic modes. Large eddy simulations are employed to investigate the connection between combustion behavior and its effects on the pressure field in CI engines. Proper orthogonal decomposition is used to analyze the modal energy distribution among acoustic modes [42, 46]. These computational techniques help in understanding the physical processes leading to combustion noise emissions.

Experimental studies explore the characteristics of combustion and exhaust emissions in CI engines using various strategies. For instance, reactivity controlled compression ignition (RCCI) is investigated by varying engine settings, piston geometry, and fuel properties to increase efficiency while maintaining ultra-low NOx and soot emissions [47]. Another study examines diesel-gasoline dual fuel combustion over a range of start of injection timings and gasoline percentages to assess combustion characteristics[48]. Single-zone zero-dimensional progressive combustion simulation models are developed to predict in-cylinder pressure, heat release rate, engine performance, and emissions characteristics. These models are validated using experimental results from engine testing with various fuels, including diesel and biodiesel blends[49]. Additionally, exhaust gas-assisted fuel reforming is explored by incorporating a laboratory reforming mini reactor in the engine exhaust system to produce hydrogen on-board [50]. The partially pre-mixed charged compression ignition (PCCI) technique is investigated using toroidal piston geometry and compared with conventional engines having hemispherical combustion chambers. Experiments are conducted with different percentages of diesel vapor and exhaust gas recirculation to study their effects on emissions and thermal efficiency [51]. Figure 4 represents variation of emission of CO with various Diesel vapor and exhaust gas recirculation

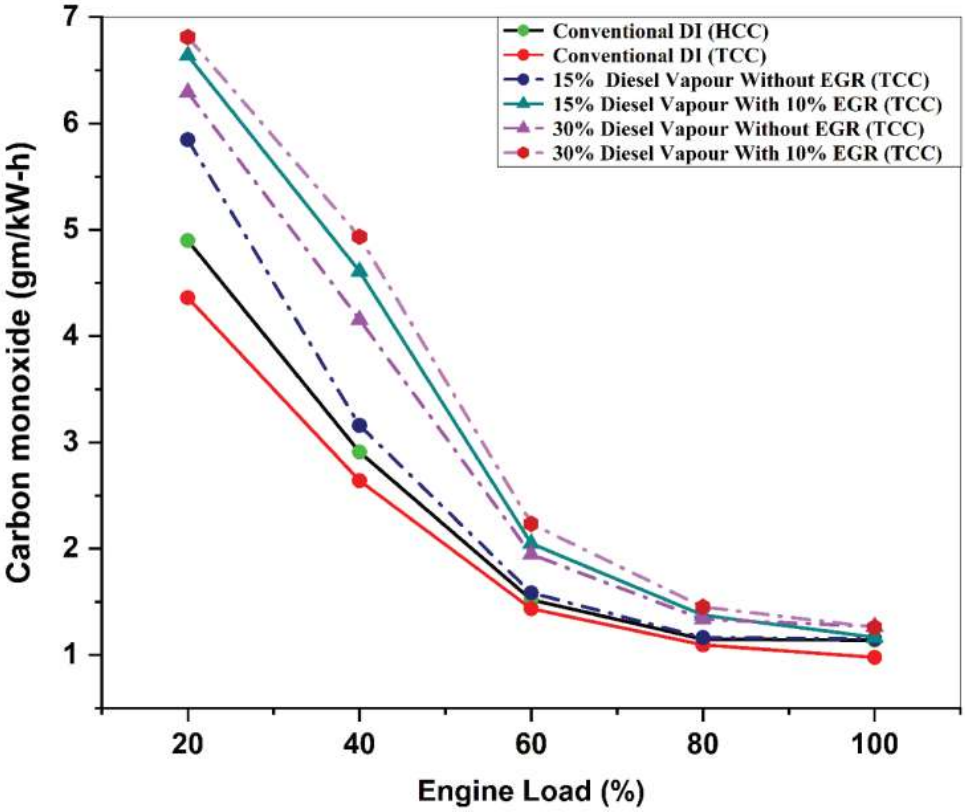

Figure 4: Variation of emission of CO with various Diesel vapor and exhaust gas recirculation

Computational Fluid Dynamic

Computational Fluid Dynamics (CFD) plays a crucial role in studying combustion and emissions in compression ignition (CI) engines, providing invaluable insights into in-cylinder conditions and processes that are difficult to observe through experimental techniques alone [52]. CFD modeling allows researchers to explore complex phenomena and optimize engine performance while reducing the need for extensive experimental testing. Computational Fluid Dynamics (CFD) simulations facilitate comprehensive analysis of various aspects of compression ignition (CI) engine operation, including spray development, auto-ignition, combustion processes, and pollutant formation [53]. Researchers can investigate the effects of diverse parameters such as injection timing, fuel properties, and engine geometry on combustion characteristics and emissions. For example, CFD studies have demonstrated that late intake valve closing can reduce NOx and soot emissions by decreasing the effective compression ratio and increasing premixing [54]. Additionally, CFD modeling has elucidated that the addition of gasoline to diesel fuel in partially premixed compression ignition (PCI) engines can retard ignition timing, lower in-cylinder temperature, and reduce exhaust emissions [55].

CFD simulations can model in-cylinder fluid motion, spray dynamics, and combustion processes (CFD Simulation of Direct Injection CI Engine Combustion and Optimization of Omega-shape Toroidal Piston Bowl Geometry for Emissions). These simulations help optimize engine design, including piston bowl geometry, to improve performance and reduce emissions (CFD Simulation of Direct Injection CI Engine Combustion and Optimization of Omega-shape Toroidal Piston Bowl Geometry for Emissions). Studies have shown that CFD can accurately predict pressure, heat release rates, and emissions, validating results against experimental data (Computational fluid dynamics simulation of the combustion process, emission formation and the flow field in an in-direct injection diesel engine). Researchers have used CFD to investigate various fuel blends, such as biodiesel mixtures, demonstrating reductions in NOx and CO emissions compared to conventional diesel [56]. Additionally, CFD analysis has been employed to study the effects of exhaust gas recirculation (EGR) on NOx and soot formation, finding an optimal EGR rate of 8.5% [57].

In the work by Engine Performance Characteristics Under Controlled Engine Temperature with Variable Operating Parameters), the authors investigated the engine performance characteristics under controlled engine temperature with variable operating parameters. The study was carried out on a three-cylinder, four-stroke, petrol, carbureted, water-cooled engine test rig connected to an eddy current type dynamometer. Another study by focused on the development of a low-NOx hydrogen-fuelled combustor for 10 MW class gas turbines, where Computational Fluid Dynamics was extensively used to model and assess the behavior of the prototype combustor and define the preliminary design of modified burners and liners Development of a Low-NOX Hydrogen-Fuelled Combustor for 10 MW Class Gas Turbines). One of the primary advantages of CFD is its capacity to provide detailed visualizations of in-cylinder processes. Researchers can utilize various visualization techniques to investigate the correlation between combustion behavior and its effects on the pressure field [41]. Furthermore, CFD simulations enable the analysis of temperature distribution, species concentrations, and emission formation throughout the combustion chamber. This level of detail facilitates the comprehension of the underlying mechanisms of combustion and emission formation, which is essential for developing strategies to enhance engine performance and mitigate pollutant emissions. CFD simulations can accurately predict in-cylinder conditions, combustion characteristics, and emission formation in engines. For example, a study on a single-cylinder diesel engine using ANSYS Forte software demonstrated the ability to simulate pressure profiles, heat release rates, and emissions of NOx, soot, and unburned hydrocarbons within a reasonable error limit of 10% compared to experimental data [52].

Computational Fluid Dynamics (CFD) analysis can capture complex phenomena like spray development, auto-ignition, combustion processes, and pollutant formation [53]. Several studies have used CFD to investigate various aspects of CI engine operation. For example, researchers have analyzed the physical processes leading to combustion noise emissions [41, 57], explored the effects of different fuels like diesel, gasoline, and ammonia[52] [58] and examined the impacts of injection timing and combustion phasing [52, 59]. CFD models have also been used to study heat transfer characteristics [60] and fluid flow patterns [59] within the combustion chamber. While gasoline-like fuels can improve the premixed charge and enable cleaner combustion than diesel, they may occasionally lead to problematic rapid increases in combustion pressure [53]. Additionally, injecting fuel near the top dead center can significantly reduce combustion instability but may also result in lower efficiency and higher emissions [59].

Nemati et al. [61] investigated gasoline-fueled CI engines, finding that double injection strategies can reduce NOx emissions [62] [63] used design of experiments to optimize CFD predictions, achieving accurate results for in-cylinder pressure, engine power, and emissions. Köten [64] examined compression ratio, valve timing, and injection parameters for single-fuel diesel engines, as well as dual-fuel compressed biogas and diesel combustion, reporting reduced NOx and particulate matter emissions[64]. Additionally, aftertreatment systems like EGR and SCR were studied to further minimize emissions. Anbarsooz (2022) reviewed the use of nanoparticles as fuel additives, reporting improvements in brake thermal efficiency and reductions in smoke and unburned hydrocarbon emissions, although effects on NOx emissions were mixed[65] .

CFD Emission characteristics & performance analysis of alternative fuels

Alternative fuels have gained attention as a means to reduce emissions and meet stricter regulations. Studies have shown that natural gas, methanol, and ethanol have the potential to lower particulate matter (PM) and nitrogen oxide (NOx) emissions compared to diesel [66]. Computational Fluid Dynamics (CFD) simulations have been used to investigate emissions from alternative aircraft fuels, such as hydrogen, ethanol, and methane, in comparison to conventional fuels [67]. For diesel engines, biofuels like Jatropha Methyl Ester (JME) and Mahua Methyl Ester (MME) have been analyzed using CFD to assess combustion characteristics and emission parameters[68] [69]. Various alternative fuels, including alcohols (e.g., butanol, octanol) and ethers (e.g., diethyl ether, dimethyl ether), have been studied as blends with conventional fuels. These alternatives often contain more oxygen, leading to more complete combustion and improved emission characteristics [70]. Biodiesel blends generally show increased brake specific fuel consumption (BSFC) and decreased brake thermal efficiency (BTE) compared to pure diesel [71, 72]. However, they demonstrate improved emission profiles, with reduced carbon monoxide (CO) and hydrocarbon (HC) emissions [70-72]. Nitrogen oxide (NOx) emissions tend to increase with biodiesel blends[70]. The higher oxygen content in alternative fuels contributes to more complete combustion, resulting in better emission characteristics[70] . Various alternative fuels studied include alcohols, ethers, and biodiesels derived from different sources such as waste cooking oil, palm oil, and jojoba [70]. Additives like ZnO nanoparticles have also been investigated for their potential to improve engine performance and emissions. Studies show that alternative fuels, particularly those with higher oxygen content, can lead to more complete combustion and improved emission characteristics. However, their lower energy content may affect overall efficiency [73]. Physical properties of fuels, such as viscosity and density, significantly influence combustion performance and emissions [74] [75]. Table 1 Illustrates various properties of Biodiesels. In aviation, blended biofuels like Camelina and Jatropha with Jet-A fuel have shown slight improvements in engine performance, with Jatropha outperforming Camelina[76]. Computational fluid dynamics modeling and experimental studies have been employed to assess the potential of these alternative fuels and their blends in various engine configurations[76] [73].

Table 1: Illustrating various properties of Biodiesels

Fuel	Kinematic Viscosity at 35°C (mm^2/s)	Pour Point (°C)	Cloud Point (°C)	Flash Point (°C)	Density (kg/m^3)	Calorific Value (MJ/kg)	Cetane Number	References
Diesel	2.65–2.73	-21	–	69–75	860	43–45	48–51	[77]
Mahua	3.98–5.72	6	–	129–209	880–916	37–39.4	–	[77]
Corn	4.363	–	–	167	885.8	39.87	55.4	[78]
Karanja	4.37–9.6	-6–5.1	-2–14.6	170–206	880–890	36.2–42.1	48–58	[79]
Palm Kernel	3.248	–	–	132	876.6	38.53	62.1	[78]
Palm	4.5–5.11	8	14	174	870–878.4	37.2–39.9	50–62	[78]
Cotton Seed	6–9.6	-4	-2	–	850–885	37.5–41.6	52	[80]
Waste Fried	4.869	–	–	168	884.2	39.68	55	[78]
Jatropha	4.23	4.2	10.2	147	873	42.673	–	[81]
Jojoba	19.2	–	–	62	866	43.38	63.5	[82]
Polanga	3.99	4.3	13.2	139	869	41.39	–	[83]
Chicken Fat	2.8	–	-7	73	869	–	48	[84]

Experimental Emission Characteristics and Performance Analysis of Alternative Fuels

Biofuels have shown promise in reducing emissions compared to conventional fuels [75, 85]. Experiments with LPG and LPG-HHO blends demonstrated improved performance and reduced emissions compared to gasoline [86]. Various alternative fuels, including alcohols and ethers, have been investigated as diesel additives, with results indicating better emission characteristics due to higher oxygen content [70]. Biodiesel blends generally show decreased engine performance but reduced emissions of HC, CO, CO_2, and particulate matter [87]. However, NOx emissions vary depending on the blend [87]. Physical properties of biofuels, such as viscosity and density, significantly influence combustion and emission characteristics [88]. Overall, alternative fuels offer potential for reducing environmental impact and ensuring energy sustainability for future generations [86, 89]. Biodiesel blends showed slightly lower performance compared to diesel, with 6-12.5% reductions in torque, brake power, and brake mean effective pressure [90]. However, biodiesel blends demonstrated improved emissions, with reductions in UHC (4%), CO (5%), and CO2 (1%) compared to diesel [90, 91].

Increasing compression ratio and injection pressure improved performance for various alternative fuels, but increased NOx emissions while decreasing HC and CO [91, 92]. Biodiesel sources did not significantly affect emissions, but neat biodiesel (B100) reduced CO, CO_2, and THC emissions by up to 15%, 40%, and 30% respectively, compared to diesel [93]. NOx emissions increased by up to 20% with biodiesel use [93, 94]. Ethanol-biodiesel-diesel blend BE20 showed the best performance and reduced emissions compared to conventional diesel [95, 96].Increasing compression ratio and injection pressure improves engine performance for various alternative fuels, but also increases NOx emissions while decreasing HC and CO emissions [92]. Compressed natural gas (CNG) as an alternative fuel reduces soot and NOx emissions in CI engines [97]. The use of additives with biodiesel can enhance performance and further reduce emissions [98]. Overall, while alternative fuels may slightly decrease engine performance, they offer significant improvements in emissions compared to conventional diesel fuel.

Effect of Nanoparticle-Blended Biodiesel

The utilization of biodiesel as an alternative fuel in compression ignition engines has gained significant attention in recent years due to its potential to reduce environmental impact [99]. One of the commonly used feedstocks for biodiesel production is used cooking oil, which can be converted into high-quality biodiesel [100]. However, the application of biodiesel in compression ignition engines is hindered by certain drawbacks such as higher viscosity, higher density, lower cloud point, inefficient fuel atomization, and higher NOx emissions. To overcome these drawbacks, researchers have investigated various techniques, including the use of fuel additives, hybrid fuels, and engine parameter modifications. NOx emissions with engine load variation is presented in figure 5.

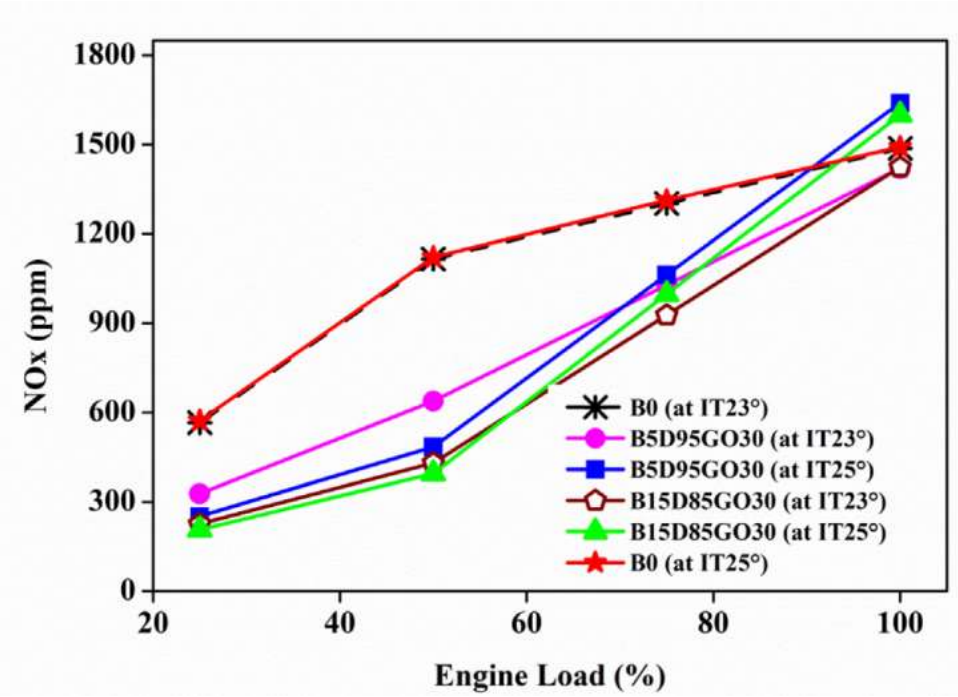

Figure 5: NOx emissions with engine load variation of bio diesel blends

One such technique is the inclusion of nanoparticle additives with biodiesel blends [101]. The addition of nanoparticles, such as graphene oxide, to biodiesel blends has been shown to enhance the combustion characteristics, leading to improved engine performance and reduced emissions. [102]. The performance and emission characteristics of the engine are influenced by the type and amount of nanoparticle additives, as well as the engine parameters. Nanoparticles such as cerium oxide, multi-walled carbon nanotubes, aluminum oxide, zinc oxide, and iron oxide have been investigated [103]. These additives generally decrease emissions of nitrogen oxides, carbon monoxide, hydrocarbons, and particulate matter. The improved performance and reduced emissions are attributed to nanoparticles' high specific surface area, better heat transfer capability, and catalytic properties. However, challenges remain, including fuel stability and the need for further research before widespread implementation [104].

Many researchers have studied the effects of nanoparticle-blended biodiesel on the performance and emissions of compression ignition engines [105, 106] [101]. The addition of nanoparticles, such as metal oxides of Cu, Fe, Ce, Pt, B, Al, and Co, has been found to improve the density, sulfur content, and volatility of the fuel, which can ultimately affect the fuel emissions[106] . The use of nanoparticle additives has been reported to enhance the combustion characteristics (figure 6), leading to improved engine performance and reduced emissions. Experiments have been conducted using diesel engines with diesel-biodiesel blends containing various nanoparticle additives. The results have shown that the addition of nanoparticles can improve engine performance parameters, such as brake power, brake thermal efficiency, and specific fuel consumption, while also reducing emissions, such as carbon monoxide, hydrocarbon, and particulate matter[101, 106].

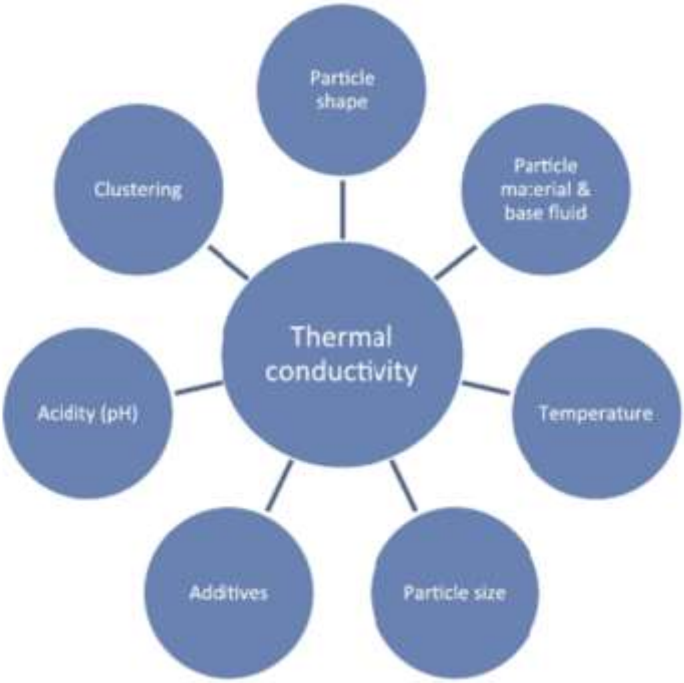

Figure 6: Factor affecting the thermal conductivity of nanofluids

Various nanoparticles, including carbon nanotubes (CNTs), copper oxide (CuO2), alumina, and cerium oxide, have been investigated. The addition of these nanoparticles to biodiesel blends generally improves engine performance and reduces emissions. CNTs increased brake thermal efficiency by 2.24% compared to biodiesel without nanoparticles [107]. CuO2 nanoparticles improved combustion and performance characteristics while decreasing exhaust emissions [108]. Alumina and cerium oxide nanoparticles reduced NO emissions by 9% and 7%, respectively, and improved brake thermal efficiency by 5% [109]. A combination of cerium oxide and titanium oxide nanoparticles (B20COTO) showed high brake thermal efficiency and reduced brake-specific fuel consumption, HC, and NOx emissions compared to other fuels [110]. These improvements are attributed to the nanoparticles' high surface area to volume ratio, which enhances combustion and fuel atomization. Experimental studies have shown that nanoparticle-blended biodiesel can significantly enhance the performance and reduce emissions in compression ignition (CI) engines. The addition of nanoparticles such as iron oxide (Fe_3O_4), alumina (Al_2O_3), and titanium dioxide (TiO_2) to biodiesel blends has been found to improve combustion characteristics and overall engine efficiency [111-113]. Table 2 illustrates the Diesel and Biodiesel Blend Engine Performance and Emissions Using Different Nano-Additives. As an example, incorporating 50 ppm of TiO_2 nanoparticles into pure biodiesel (B100T50) resulted in a 5.2% increase in brake thermal efficiency and a 10.56% decrease in brake-specific fuel consumption when compared to pure biodiesel. Furthermore, substantial reductions in emissions were noted, with CO, HC, and smoke emissions dropping by 44%, 28%, and 44%, respectively [112]. In a similar vein, blending CeO_2 and Al_2O_3 nanoparticle mixtures with biodiesel enhanced overall performance, emission characteristics, and combustion efficiency [94, 111]. Notably, while the majority of biodiesel fuels mixed with nanoparticles demonstrated decreases in carbon monoxide, hydrocarbon, and smoke emissions, certain studies observed an uptick in nitrogen oxide (NOx) emissions. As an illustration, reported a 21% rise in NOx emissions when comparing nanoparticle-blended biodiesel to pure biodiesel at maximum load. Nevertheless, additional research has indicated that employing exhaust gas recirculation (EGR) alongside nanoparticle-blended biodiesel can assist in counteracting the increase in NOx emissions[114] .

Table 2: Diesel and Biodiesel Blend Engine Performance and Emissions Using Different Nano-Additives

Engine Specification	**Engine Speed & C.R**	**Loading and Swept Volume**	**Biodiesel Blend**	**Nano-particles & Particle Size**	**NPs Dosage and Surfactant**	**Ref**
Diesel engine	2500 rpm	-	POME	Graphene oxide (50 nm)	10 ppm	[115]
Kirloskar TV1, single cylinder, 4-stroke DI engine	1500 rpm, 17.5:1	POME (B20)	Ferrous oxide, ferrofluid (100 nm)	0.5%, 1%, 1.5%		[116]
Kirloskar, single cylinder, 4-stroke DI engine	1500 rpm, 17:1	Electrical dynamometer	CIMME	TiO_2 (30-40 nm)	40 ppm	[117]
DEUTZ F1L511	-	4-stroke DI engine	HOME	Cerium oxide (25 nm)	30-50 ppm	[118]
HATZ-1B30-2, 4-stroke DI	1500 rpm, 21.5:1	-	Graphene oxide	30-90 ppm		[118]

AV1- Kirloskar, 4-stroke single- cylinder	1500 rpm, 16.5: 1	553 cc	POME	Aluminum oxide (100nm)	50-100 ppm	[119]
AV1 Kirloskar, 4-stroke, single cylinder	1500, 16.5: 1	553 cc	POME	Aluminum oxide (100nm)	50-100 ppm; Cetyltrimethylammo nium bromide	[119]
WD Engine	2500 rpm	-	WDA (water diesel)	SiO_2 (20-30 nm)	20-50 ppm	[120]
HOME-based biodiesel	1500 rpm	-	Biodies el with cerium oxide	40 ppm	-	[121]]
Cummins Diesel Engine, 4-stroke diesel engine, TC, Euro 5	2500 rpm	-	POME	Carbon coated aluminum (Al@C)	30 ppm; 4% ethanol	[122]
Kirloskar TV1, vertical single cylinder	1500 rpm, 17:1	661 cc	CIMM E	Titanium dioxide (TiO2) (30-40nm)	40 ppm; Cetyl bromide (CH3)3NH4	[123]
Single cylinder DI, water-cooled	1500 rpm, 17.5: 1	661.45 cc	20% HOME	Coconut shell additives, 20 nm	-	[124]
Urea-SCR equipped DI engine, 4-cylinder	2000 rpm, 17.9: 1	Electrical generator	Waste frying oil	Mn_2O_3 and Co_3O_4 (30 nm)	50 ppm Mn_2O_3, 50 ppm Co_3O_4	[125]
Simpson-S217, 4-stroke DI engine	2000 rpm, 18.5: 1	-	CIME	Zinc oxide, ethanolox (ZnO)	20-100 ppm	[122]
Kirloskar, 4-stroke single-	1500 rpm, 17:1	661 cc	JME (B20)	Al_2O_3 nanopartic	25 ppm	[126]

cylinder diesel				les (28-30 nm)		

Conclusion

Metallic nanoparticles provide a potential way to improve engine efficiency and lower emissions when added to biodiesel mixes. Even though studies have shown promising results, more research is required to maximise the dosage and combination of nanoadditives. The behaviour of nano-biodiesel fuels in different engine components may be better understood with the use of computational fluid dynamics (CFD) simulations. Researchers may learn more about how nanoparticles affect spray production, mixing, heat release, emissions, and overall engine efficiency by modelling fuel injection, combustion, engine performance, and nanoparticle dispersion. However, to guarantee the accuracy of CFD results, multi-scale interactions, precise modelling of nanoparticle characteristics, and experimental validation are essential. The potential advantages of hybrid nanoparticles, which might improve the efficiency and environmental benefits of nano-biodiesel fuels, should also be investigated in future studies.

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