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Performance and Emissions of Nanoadditives in Diesel Engine: A review

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ABSTRACT

Nowadays, the demand for energy and fossil fuels has widely increased as a result of the continuous growth of the population. However, the continued use of traditional fuels as the primary source of energy has resulted in various environmental challenges related to climate change and global warming. This has prompted researchers to look for more eco-friendly and sustainable fuel alternatives with a minimal amount of engine modification and emission treatment techniques. Amongst the suggested alternative fuels, biofuels, biofuel/diesel blends, and the incorporation of nanoparticles into fuels. The nanoparticle diesel additives played a vital role in increasing engine performance as well as retarding harmful emissions such as nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbon (UHC), and particulate matter (PM). Metal-oxides nanoadditive such as aluminum oxide (Al2O3), ceric oxide (CeO2), and titanium dioxide (TiO2) act as oxygen catalysts and promote proper mixing of fuel and air, resulting in more efficient combustion and decreased emissions. The incorporation of nanometal-based additives, including iron (Fe), copper (Cu), and aluminum (Al) accelerated the fuel evaporation rate and increased the probability of fuel ignition. Carbon-based nanoparticles such as carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), and graphene oxide (GO) are promising fuel nanoadditives owing to their metal-free composition. In addition, carbon-based additives enhanced the thermal conductivity of fuel and increased active sites available for chemical reactions, which led to improved engine performance.

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1. INTRODUCTION

Currently, the world is facing two major problems: environmental degradation and the depletion of fossil fuel reserves. Fossil fuels have a great deal of drawbacks, including being non-renewable energy sources and harmful to the environment. Combustion of fossil fuels produces carbon oxides and nitrogen oxides into the atmosphere, contributing to the greenhouse effect and causing an increase in global temperatures [1]. More enhanced combustion indicates more fuel being burned, resulting in greater exploitation of the stored chemical energy of the fuel and lower emissions. In contrast, poor combustion results in incomplete combustion of fuel, releasing more hazardous emissions, including carbon monoxide, nitrogen oxide, and sulphur oxide. It can also result in the release of more smoke into the atmosphere and the creation of smog.

The efficiency of combustion in a diesel engine is strongly dependent upon the properties of the fuel being utilized. Improved fuel properties such as cetane number, viscosity, thermal conductivity, and heating value have been found to boost diesel engine performance and lower emissions [2], [3]. This triggered research on discovering more sustainable, biodegradable, and non-toxic alternative fuels that can be used in diesel engines with the least amount of engine modifications [4]–[7]. The incorporation of nanoadditives in diesel, biodiesel, and diesel/biodiesel fuels has been found to be a promising and optimistic approach to enhance the overall engine performance and reducing harmful pollutants. Nanoadditives played a vital role in improving fuel combustion by adulterating fuel properties such as cetane number and caloric value, which are important indicators of fuel quality. Also, nanoparticles can increase the surface area of fuel particles, resulting in an increase in the rate of fuel droplet evaporation and catalytic activity. This maximizes the combustion efficiency, which leads to a more complete and efficient burning of fuel and consequently lower emissions of dangerous pollutants [8], [9]. An approach used to enhance engine performance is to improve the tribological properties of engine oil by using nanolubricants. The utilization of titanium dioxide and silicon dioxide nanoadditives minimized engine losses resulting from friction and wear of internal engine components by lowering the friction coefficient and wear rate by up to 40% and 50%, respectively, with increasing temperatures in comparison to pure engine oil [10], [11].

2. NANOADDITIVES TYPES

Nanoparticles come in different ranges of shapes (flat, tubular, spherical, cylindrical, or irregular shapes), sizes (1 to 100 nanometers), and structures. Also, nanoparticles come in a variety of configurations; zero-dimensional (nano dots), one-dimensional (graphene), two-dimensional (carbon nanotubes), and three-dimensional (gold nanoparticles). Nanoparticles can be carbon-based (organic), or inorganic, such as metal, metal oxide nanoparticles [12].

2.1. Metal oxide-based nanoadditives

Nanometal oxides, including but not limited to aluminum oxide (Al2O3), magnesium oxide (MgO), titanium dioxide (TiO2), copper oxide (CuO), and manganese (II) oxide (MnO), have been utilized as additives for diesel fuel with the objective of improving the combustion process [13]. These nanoparticles function as catalysts, which assist in the decomposition of carbon monoxide by supplying oxygen. Also, the addition of nanometal oxides causes a greater absorption of oxygen, which eventually results in lower NOx, HC, and PM emissions. The presence of metal oxide nanoparticles with higher oxygen content has been found to lower emission levels and also ensure more efficient combustion. Proper air/fuel mixing is critical for proper combustion. These nanoparticles have been shown to enhance fuel-air mixing and improve atomization and evaporation rates. These effects ought to be attributed to the larger air/fuel surface area caused by the nanoparticles [14].

Researchers have demonstrated that nanoadditives with an excess of oxygen can enhance fuel combustion by creating an additional possibility for the oxidation of unburnt fuels in the cylinder [15]. The utilization of zinc oxide (ZnO) as a nonadditive has been found to enhance fuel properties such as cetane number and heat absorption, thereby leading to a reduction in the emission of nitrogen oxides (NOx). The oxidation of fuel is augmented by the high catalytic activity of ZnO nanoparticles, which increases the surface-to-volume ratio of the nanoadditives, resulting in reduced smoke emissions. Al2O3 nanoparticles, in general, function as great combustion catalysts, lowering pollutant emissions while increasing combustion efficiency. The blending of Al2O3 nanoparticles has been observed to boost engine power by promoting a higher oxidation rate, increasing in-cylinder pressure, and lowering both ignition temperature and ignition delay, resulting in lower HC and CO emissions. TiO2 nanoparticles showed a great increase in combustion rate owing to their high surface energy. The enhancement of combustion efficiency by adding TiO2 nanoparticles is linked to the improvement of thermal conductivity, which subsequently results in an increase in radiation heat transfer rate and an improved evaporation rate [16].

2.2. Metal-based nanoadditives

Metallic nanoparticles are desirable choice as fuel additives due to their high reactivity and energy density. Nanometal additives such as iron (Fe), copper (Cu), titanium (Ti), aluminum (Al), zinc (Zn), and manganese (Mn), were used as catalysts to accelerate the combustion process and decrease emissions. The incorporation of nanometal particles into fuel has been observed to increase the heat transfer rate, leading to an accelerated fuel evaporation process and a higher probability of fuel ignition. These factors contribute to a decrease in ignition delay [17].

Nanometal-based additives have been demonstrated to decrease emissions by reacting with water vapor in the engine exhaust to form extremely reactive hydroxyl radicals. These hydroxyl radicals may then react with and breakdown hazardous pollutants in the exhaust, resulting in lower emissions. Also, Metal-based can act as oxidation catalysts, decreasing the oxidation temperature of soot to promote more complete combustion. As a result, fuel particles burn increase, resulting in a reduction in particulate matter emissions [18].

2.3. Carbon-based nanoadditives

Carbon nanotubes (CNTs) are commonly utilized as sustainable additives owing to their non-metallic composition. Carbon nanotubes are metal-free carbon-based nanomaterials. Carbon nanotubes have been observed to improve the cetane number and boost the combustion rate of fuel through their catalytic properties [19]. CNTs have also been found to cause shorter ignition delays and improve combustion characteristics, which led to improved engine performance [20]. CNTs have also been shown to increase spray properties and lower combustion temperatures, leading to more efficient combustion [21]. Additionally, the incorporation of carbon nanotubes in fuel has been found to provide various advantages for engine efficiency and emissions. Moreover, the enhanced thermal conductivity exhibited by CNT nanoparticles has the ability to increase the evaporation rate of water particles in emulsion fuel, particularly during the pre-mixed phase, and increase the rate of heat transfer during the combustion process. This, in turn, can lead to a shorter ignition delay period and enhance overall engine performance [22]. CNTs have also been found to cause shorter ignition delays and improve combustion characteristics, which led to improved engine performance. The utilization of CNT nanofuel has been observed to reduce combustion pressure, thereby resulting in a decrease in the formation of NOx [23].

Graphene nanoplatelets (GNPs) are compacted multilayers of two-dimensional sheets made up of up to ten layers of graphene. On the other hand, graphene oxide (GO) is formed by graphene oxidation, which introduces functional groups containing oxygen onto the surface of the graphene sheets.

The addition of GO nanoparticles and GNPs to fuel has been observed to enhance the combustion process and raise in-cylinder pressure. GO nanoparticles provided higher thermal conductivity as well as a larger surface area, which helped promote the combustion process and consequently reduced fuel consumption. In addition, incorporating GO nanoparticles into fuel lowered the ignition delay, increased thermal efficiency, and reduced CO and UHC emissions [24]. Also, when GO nanoparticles are used, a CO/CO2 balance is achieved, with a reduction in CO emissions accompanied by an increase in the generation of CO2. However, the incorporation of GO nanoparticles may result in a rise in NOx emissions as a consequence of the higher pressure and temperature within the cylinder.

The high chemical reactivity of GO nanoparticles is a desired property that may be utilized to enhance fuel combustion efficiency and lower harmful emissions. The increased surface area of the GO nanoadditive raises their chemical reactivity, resulting in more exposed sites available for chemical reactions, which can lead to a reduction in ignition delay, lowered CO levels, and promoted combustion [25].

3. NANOADDITIVES EFFECTS ON ENGINES PERFORMANCE

This section summarizes the influence of adding nanoparticles on engine performance.

3.1. Break specific fuel consumption (BSFC)

Break specific fuel consumption (BSFC) is a crucial engine performance parameter that indicates how efficiently the quantity of fuel supplied to the engine gets converted into shaft power output [2].

Ahmed *et al.* [26] reported that as engine speed rises, so does brake specific fuel consumption (BSFC). However, adding graphite (G) and iron oxide (Fe2O3) nanoparticles to pure diesel could decrease engine BSFC, as demonstrated in Fig. 1. Moreover, the BSFC decreases as the concentration of fuel additives increases. The highest decreases in BSFC were 2.2% and 2.6% for 150 mg/l for both Fe2O3 and G, respectively.

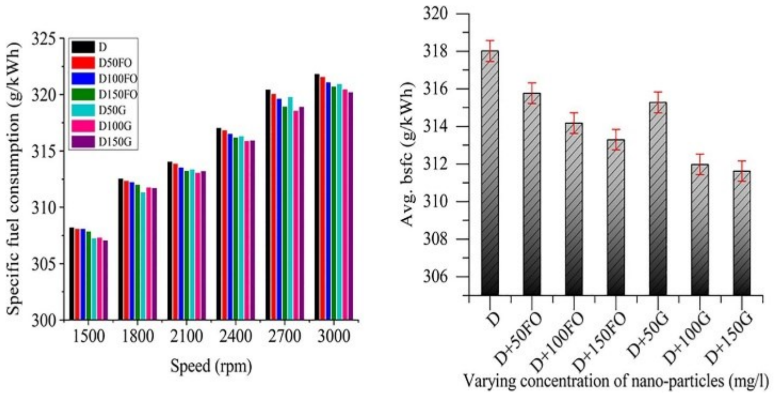

Fig. 1. Influence of Fe_2O_3 and G nanoparticles concentrations on BSFC and average BSFC at different engine speeds [26].

Yaşar *et al.* [27] evaluated the impact of adding metallic-based nanoparticles to neat diesel at 25 and 50 ppm under compression ratios of 17:1 and 18:1. Nanoadditives used were copper(II) nitrate (Cu(NO3)2), titanium(IV) dioxide (TiO2), and cerium(III) acetate hydrate (Ce(CH3CO2)3·H2O). In general, it was observed that the incorporation of metallic additives led to a decrease in BSFC as a result of the improved calorific value of the fuel and the greater surface area that promoted complete combustion. DTiCeA100 (diesel+50ppm TiO2+ 50ppm Ce(CH3CO2)3·H2O) fuel blend showed the maximum BSFC reduction of 12.21% at a compression ratio of 18 [27]–[29].

Blending Al2O3 and CuO nanoparticles into diesel fuel lowered BSFC at all engine speeds, as illustrated in Fig. 2. The oxygen content of these nanoparticles promotes combustion efficiency. Consequently, this results in a decrease in BSFC. Maximum decreases in BSFC were 0.5% and 1.2% for D+50 ppm CuO and D+50 ppm Al2O3, respectively [30].

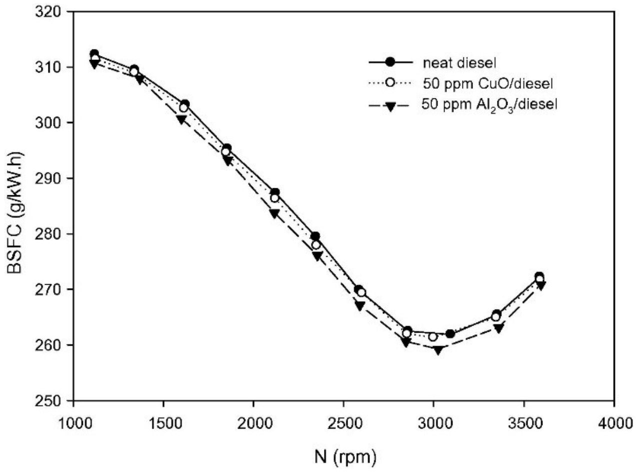

Fig. 2. BSFC as a function of engine speed for neat diesel and diesel containing CuO and Al_2O_3 nanoparticles [30].

The BSFC of emulsion fuels containing nanoadditives was observed to be lower than that of E10 at BMEPs of 0.928, 4.333, and 5.262 bar. At all BMEPs, E10Al2O3 and E10CuO consistently had lower BSFC than E10. The lower calorific value and the decreased heat losses of the of the fuel blends were the primary factors leading to the rise in BSFC. At higher BMEPs, the higher in-cylinder temperature leads to improved combustion resulting in a lower BSFC. The highest reduction reported was 5.5% for E10Al2O3 at a BMEP of 5.262 bar [31], [32].

3.2. Break thermal efficiency (BTE)

Break thermal efficiency (BTE) refers to the efficiency at which heat is converted into shaft power and is defined as the ratio of the engine's brake power output to the fuel energy supplied to the engine [27].

Saxena *et al.* [2] added G and Fe2O3 nanoparticles at mass fractions of 50, 100, and 150 mg/l. The results indicate a positive correlation between the doze of nanoparticles in fuel and the improvement of BTE. This is most likely due to increasing nanoparticle reactivity as well as their increased surface area. Also, dosing nanoparticles improved fuel thermal conductivity. The maximum BTE increased by 26.1% for the D150G.

Gumus *et al.* [30] synthesized nanodiesel by blending Al2O3 and CuO nanoparticles at 50 ppm mass fraction to the standard diesel fuel. The study found that the power output of the engine increases with an increase in engine speed, regardless of the fuel used. Also, adding nanoparticles to diesel fuel enhances engine power in comparison with standard diesel fuel due to an accelerated oxidation rate and shorten ignition temperature. According to their findings, Al2O3 yielded better results than CuO. The maximum increases in torque reported were 3.28% and 1% for 50 ppm Al2O3 and CuO, respectively.

Dhahad and Chaichan [33] evaluated the effect of adding Al2O3 and ZnO nanoparticles to Iraqi diesel fuel at 50 and 100 ppm mass fractions. According to their findings, increasing engine load and the concentration of nanoparticles in fuel increased in engine's BTE as shown in Fig. 3. The maximum increases in BTE reported were 5.4 and 6.3% for D+100ZnO and D+100Al2O3, respectively. Also, D+Al2O3 demonstrated superior BTE increment in comparison to D+ZnO due to a lower BSFC, a maximum of 6.9% and 7.83% for D+100ZnO and D+100Al2O3, respectively.

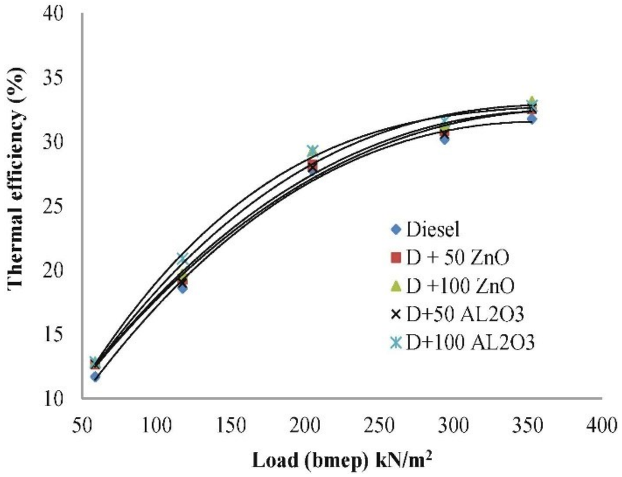

Fig. 3. The thermal efficiency of diesel engine with Al_2O_3 and ZnO nanodiesel at various engine loads [33].

Liu *et al.* [34] shows that the increased catalytic activity of CeO2 nanoparticles at higher temperatures results in a decrease in the activation energy necessary for the combustion of diesel fuel blends. Furthermore, CeO2 nanoparticles have been found to have the ability to act as an oxygen buffer, which means that they can release oxygen and promote complete combustion of the catalytic diesel. Fig. 4 depicts the change of in-cylinder pressure, heat release rate, and pressure increase rate versus crank angle for pure diesel, and diesel blended with 50 and 100 mg/l CeO2 at the speed of 3200 rpm and full engine load.

In the in-cylinder pressure curve, the maximum in-cylinder pressure of catalytic diesel increases, with the peak phase approaching the top dead center (TDC). According to the results, the maximum in-cylinder pressures belonged to the D+100CeO2 blend. The peak combustion pressures developed with D+50CeO2 and D+100CeO2 blends were improved by 1.25% and 2.98%, respectively, compared with neat diesel. Results showed that increasing the proportion of nanoparticles further increased the maximum cylinder pressure.

The heat release rate (HRR) curve shows that for all fuel blends, the heat release rate increased when compared to neat diesel fuel. Based on the findings, it can be concluded that D+100CeO2 exhibited the highest heat release rate. This is due to the shortened ignition delay period leading to an accelerated fuel combustion rate, which results in more effective combustion when compared to pure diesel fuel. The results suggest that the increase in surface energy resulting from the addition of CeO2 nanoparticles allows for higher nanoparticle-fuel droplet collisions. This results in higher thermal conductivity for diesel molecules. This led to proper atomization and combustion of the fuel spray and promoted the chain reaction, resulting in higher combustion rate. Also, it can be seen that the combustion starting points advanced by 0.3 °CA and 0.6 °CA for D+50CeO2 and D+100CeO2, respectively, due to chain combustion.

The in-cylinder pressure, pressure rise rate, and heat release rate curves exhibit similar trends. That is, all characteristic curves move forward upon increasing CeO2 nanoparticle dosing. This is mostly owing to the decrease in ignition delay and more promoted combustion.

Çelik *et al.* [35] added organic-based manganese nanoparticles to the neat diesel fuel and studied their effect on the engine's performance. Different doses of manganese nanoparticles ranging from 4 to 16 ppm in increments of 4 ppm were blended into the pure diesel fuel. The addition of an organic-manganese additive resulted in enhancements in engine power and torque, as indicated in Fig. 5. These improvements are attributed to the catalytic properties of organic-based manganese nanoparticles, which allow the separation of fuel into smaller hydrocarbons, which break down complex hydrocarbons into smaller hydrocarbons [36]. The catalytic cracking effect of these nanoadditives is caused by the presence of active manganese sites on the catalyst's surface. This improves the air/fuel mixing [37], [38]. The greatest power and torque improvements occurred at a manganese concentration of 12 ppm.

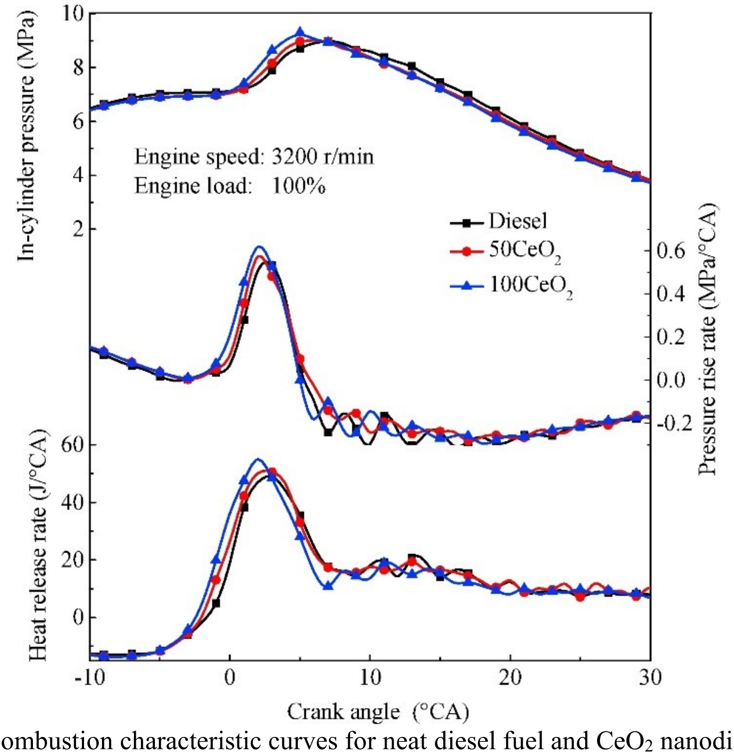

Fig. 4. Combustion characteristic curves for neat diesel fuel and CeO_2 nanodiesel [34].

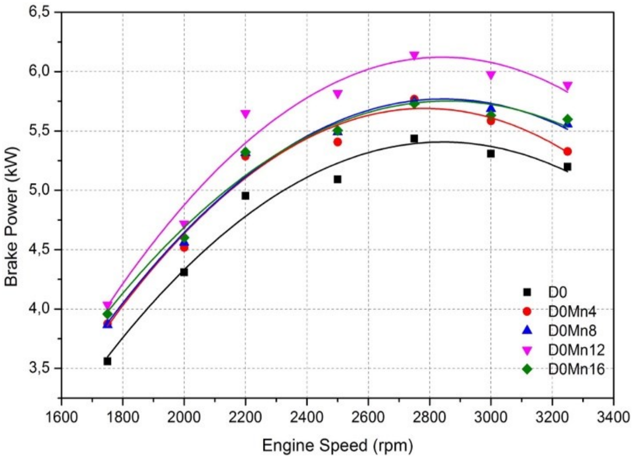

Fig. 5. The Influence of manganese nanoparticles on brake power variations at full engine load [35].

4. NANOADDITIVES EFFECTS ON ENGINES EMISSIONS

This section presents the impact of adding nanoparticles on engine emissions.

4.1. Nitrogen oxides (NOx)

Oxides of nitrogen (NOx) are harmful gases composed of nitrogen and oxygen. Nitrogen oxides contribute to air pollution and are a major component of smog and acid rain [27].

According to Ahmed *et al.* [26], Fe2O3 and G nanoparticles raised emissions of NOx. As seen in Fig. 6, NOx emissions are at their peak at 2400 rpm, when the engine delivers the maximum torque, which results in greater combustion and higher temperatures and consequently increases NOx. On the other hand, NOx decreases with higher engine speeds, notably between 2700 and 3000 rpm. The reason for this is probably because, at higher speeds, the engine does not have enough time to complete the combustion. This means a lower residence time of the air/fuel mixture within the cylinder. The maximum percentage increases observed were 34.7% and 29.2% for 150 mg/l for both Fe2O3 and G, respectively.

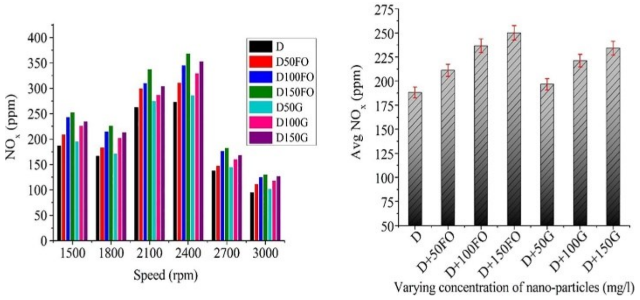

Fig. 6. NO$_x$ and average NO$_x$ as a function of engine speed for pure diesel and Fe_2O_3 and G nanodiesel fuels blends [26].

Yaşar *et al.* [27] looked at the NOx emissions of diesel fuel containing nanometal additives. For a lower compression ratio (17:1) and lower load (4 Nm), the largest decrease in NOx was observed to be 27.77% for DTiCeA50. For all fuel blends NOx emissions are found to increase upon increasing compression ratio and engine load due to elevated in-cylinder pressure and temperature.

Gumus *et al.* [30] reported that NOx was reduced by blending Al2O3 and CuO to neat diesel. The maximum reductions of NOx were 6% and 2% for Al2O3 and CuO, respectively.

Soukht Saraee *et al.* [39] added cerium oxide (CeO2) nanoadditives to neat diesel in three mass fractions (10, 20, and 40 ppm). A significant decrease in NOx was observed resulting from lowered in-cylinder temperature caused by promoted combustion owing to the high catalytic activity of CeO2. Also, the concentration of NOx decreases as the amount of blended nanoparticles increases, as demonstrated in Fig. 7. In accordance with their findings, DC40 (Diesel+40ppm CeO2) exhibited the maximum NOx reduction of 42.7%.

Gad and Jayaraj [40] blended 20% Jatropha biodiesel (J20) with diesel fuel and employed nanoadditives such as CNTs, TiO2, and Al2O3. The results indicated that increasing oxygenated additive contents decreased NOx emissions due to promoted combustion and a shorter ignition delay. They reported that NOx emissions were reduced by 52%, 35%, and 35% for J20C50, J20T25, and J20Al100, respectively.

El-Seesy, Attia, *et al.* [41] studied the blending of alumina nanoparticles (Al2O3) with amounts of 10 to 50 mg/l in a step of 10 mg/l into the Jojoba biodiesel-diesel (JB20D) fuel blend. They reported remarkable NOx reductions of 70% for JB20D20A (Jojoba biodiesel/diesel+20 mg/l of Al2O3) when compared with JB20D blended fuel. This might be attributed to Al2O3 nanoparticles catalytic behavior, which enables complete combustion with lower in-cylinder pressure. As engine loads increase, the in-cylinder temperature rises, resulting in higher NOx.

El-Seesy, Hassan, *et al.* [42] investigated the influence of incorporating GNPs into the J20D80 (20% jatropha methyl ester+80% diesel) fuel blend at concentrations of 25 to 100 mg/l at 25 mg/l increments. Results showed NOx reduced by 23% at an engine speed of 1500 rpm and a GNP doze of 25 mg/l. On the other hand, at 2000 rpm, NOx reduced significantly by 55% due to decreasing combustion duration at the same amount of GNP additive. A shorter combustion period increases GNPs' catalytic effect, allowing more low-active radical formation.

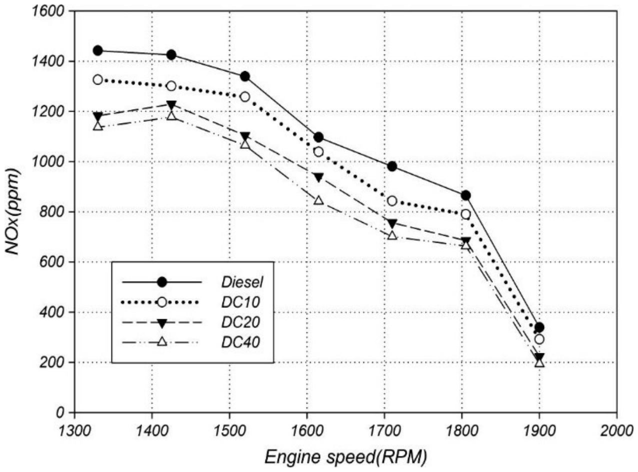

Fig. 7. Influence of CeO_2 nanodiesel on NOx variations [39].

4.2. Carbon monoxide (CO)

Carbon monoxide (CO) is a non-desired and harmful gas produced throughout the incomplete combustion [27].

Ahmed *et al.* [26] showed that the minimum CO levels occurs when the engine is operating at 2400 rpm. The quantity of CO emissions reduced as the consumption of fuel particles increases. CO emissions, on the other hand, tend to rise as engine speed rises. This is because there is not enough time for fuel/air mixing. The findings also indicate that a rise in Fe2O3 and G dozes in diesel decrease the CO emissions. The maximum CO reduction reported were 9.8% and 14.2% for 150 mg/l for both Fe2O3 and G, respectively.

Yaşar *et al.* [27] reported that for all fuels with nanoadditives, CO emissions were lower compared to diesel owing to enhanced thermal conductivity. DTiCeA100 showed a maximum reduction in CO of 23.23% under 8 Nm load and a compression ratio of 17:1. Increasing the compression ratio improves the catalytic activity of the fuel, allowing for more complete combustion. The highest reduction in CO emission was 43.24% for DTiCeA100 under 8 Nm load and compression ratio 18:1.

Mixing neat diesel fuel with Al2O3 and CuO at 50 ppm showed higher CO reductions. This decrement becomes higher at higher BMEPs. On the other hand, CO decreases upon the addition of nanoparticles. This could be caused by the better fuel distribution in the cylinder. The maximum reductions of CO were 11% and 8% for Al2O3 and CuO, respectively. The findings further demonstrated that the use of Al2O3 nanoparticles reduces CO emissions even more compared to CuO. This is likely due to the greater decrease in ignition delay time produced by employing Al2O3, resulting in more proper combustion than CuO nanoparticles [30].

Hasannuddin *et al.* [31] reported that across all BMEPs, brake specific carbon monoxide (BSCO) emissions were significantly higher for E10 fuel in comparison to neat diesel by 18.6%. Still, as the BMEP increased, the differential in BSCO emissions reduced. The higher BSCO emissions were caused by a lower combustion temperature as a result of the presence of water or poor air/fuel mixing. The utilization of fuel with a lower calorific value and a longer ignition delay enhanced BSCO. The oxygen concentration in E10 may boost oxygen availability at 5.262 bar BMEP. As a result, BSCO emissions were reduced. E10ZnO provided the maximum BSCO reduction by 17%.

At full engine load, CO emission maximum reduction was 51.76% for D0Mn12. In addition, D0Mn12 showed the lowest CO emissions for all loads. Results showed that as the load increased, so did the CO emissions [35].

El-Seesy, Hassan, *et al.* [42] noticed that increasing engine speed decreases CO emissions. At higher engine speeds, better air/fuel mixing allows for an increasing rate of CO oxidation with elevated gas temperatures. CO was reduced by 55% and 65% for 25 mg/l GNP at 1500 and 2000 rpm, respectively.

Kumar *et al.* [43] used diethyl ether and CeO2 nanoadditives with waste cooking oil (WCO) biodiesel at 20-40% blends. Results showed that using neat WCO would produce higher CO emissions compared to WCO with nanoadditives as indicated in Fig. 8. This is owing to the uniform air/fuel mixing and higher viscosity, resulted in uneven fuel combustion. With higher blends of neat WCO, CO is reduced due to oxygen contained in the fuel, which promotes combustion. The maximum CO reduction found was 52% for B40DEE5C (biodiesel 40%+diesel 70%+diethyl ether 5%+80 ppm cerium oxide).

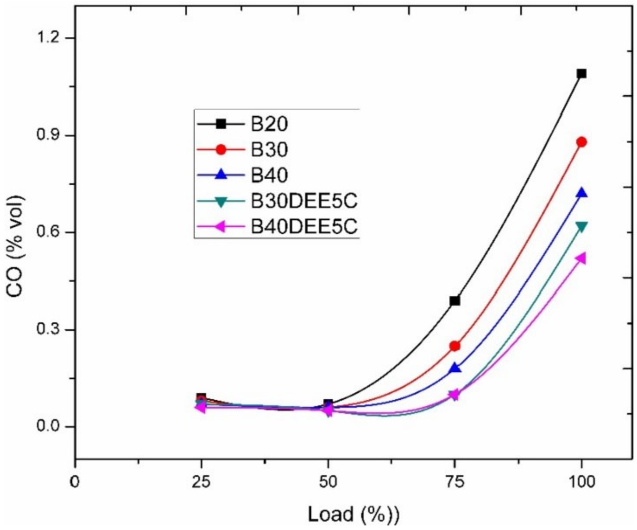

Fig. 8. Influence of increasing WCO biodiesel blend and adding CeO_2 nanoparticles to WCO/DEE fuel on CO emissions [43].

EL-Seesy *et al.* [44] studied the effects of adding GO nanoparticles to Jatropha methyl ester (JME). Graphene oxide additives are one of the most promising fuel additives owing to their low toxicity since GO is carbon-based. The results revealed that the incorporation of GO into JME significantly decreased CO emissions. The optimum GO concentration for achieving the maximum reduction of CO (60%) is 50 mg/l GO.

Akram *et al.* [45] conducted an experimental study to investigate the influence of CeO2 and Ce0.5-Co0.5 nanoadditives on the different biodiesel blends. The results illustrated that CO was reduced with higher biodiesel blends. Also, the cerium nanocomposite oxide demonstrated superior CO reduction in comparison to CeO2. Compared to neat diesel, the maximum CO reduction of 36.08% was obtained for 100 ppm of cerium nanocomposite oxide.

Mirzajanzadeh *et al.* [46] examined the influence of cerium oxide on amide-functionalized multiwall carbon nanotubes (MWCNT-CeO2) hybrid nanocatalyst to B5 and B20 diesel/biodiesel blends. The findings indicated less CO was emitted for nanoadditive concentrations for both B5 and B20. The maximum CO reduction reported is 38.8% for B20 + 90 ppm MWCNT-CeO2.

Praveen *et al.* [47] examined experimentally the extent to which the influence of adding TiO2 nanoparticles to a 20% Calophyllum Inophyllum diesel/biodiesel blend (B20). The study reveals that, with the exception of the full load condition, an increase in load leads to a reduction in CO emissions. Also, the use of TiO2 nanoparticles improved air/fuel mixing and shortened the ignition delay, which promotes fuel combustion. The maximum CO reduction was 23% for B2040TiO2.

4.3. Unburned hydrocarbon (UHC)

Unburned hydrocarbon (UHC) emissions occur when hydrocarbons are released into the atmosphere without being fully burned during combustion [27].

Yaşar *et al.* [27] indicated that HC emissions for neat diesel were higher than diesel with nanoadditives. This might be owing to the higher catalytic characteristics of TiO2 and cerium(III) acetate nanoparticles and better fuel combustion. The maximum reduction in HC emissions recorded was 23.25% for DTiCeA100 under 4 Nm load and compression ratio 17:1. Moreover, further increasing the compression ratio will result in a further decrease in HC emissions and enhanced combustion. DTiCeA100 reduced HC emissions by up to 45% as compared to pure diesel fuel.

Gumus *et al.* [30] have demonstrated that blending Al2O3 and CuO to diesel fuel reduced HC levels in comparison to pure diesel. Al2O3 showed lower HC emissions than CuO. This could be due to the enhanced ignition properties and reduced ignition delay of aluminum oxide nanoparticles. The maximum reductions in HC were 13 and 5% for Al2O3 and CuO, respectively.

Hasannuddin *et al.* [31] observed that the brake specific hydrocarbon (BSHC) emissions decreased with increasing BMEP for all fuels. A higher BMEP indicates higher local oxygen that promote combustion and provide higher cylinder temperatures that could promote the oxidation of hydrocarbons. BSHC emissions were higher at low BMEPs (0.928 and 2.166 bar), as indicated in Fig. 9, due to poor fuel distribution and the escape of lean fuel/air mixture from the cylinder. The high hydrocarbon (HC) emissions observed in E10 and nanoadditive emulsion fuel could be attributed to their lower cetane numbers, and longer ignition delay caused by the presence of water in the fuel. As a result, cylinder temperature reduced, resulting in insufficient ignition of unburned fuel. This led to incomplete combustion and a subsequent increase in BSHC emissions. The BSHC emission was found to be influenced by the characteristics of E10 and nanoadditive emulsion fuel, including higher density and viscosity, compared to pure diesel.

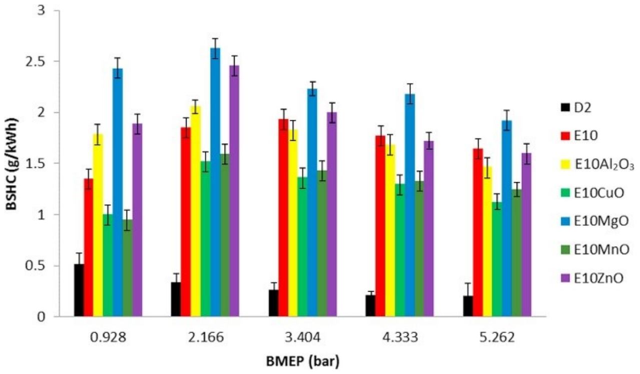

Fig. 9. Influence of Al_2O_3, CuO, MgO, MnO, ZnO nanoparticles on BSHC as a function of BMEP [31].

Manganese nanoparticles showed a maximum HC emission of 6.41% for D0Mn12 in comparison to neat diesel. The results indicate that as the load increases, there is a corresponding rise in HC emissions [35].

4.4. Particulate Matter (PM)

Particulate Matter (PM) emissions refer to the release of microscopic solid or liquid particles into the air. PM emissions from engines are typically classified according to their size, with smaller particles generally being more harmful to human health [27].

Adding nanoadditives to water in diesel emulsion fuel reduced brake specific particulate matter (BSPM) emissions. In comparison with neat diesel, emulsion fuels containing nanoadditives produced less BSPM. E10 and E10ZnO showed the highest decrease in BSPM, up to 65% lower than D2 as presented in Fig. 10. The major factors for the lower BSPM emissions were the increased amount of diesel emulsion fuel and the consumption of soot precursors by oxygen [31].

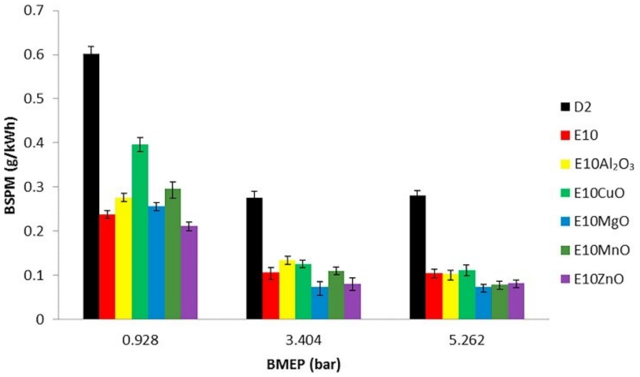

Fig. 10. BSPM variations for D2, E10, and E10+nanoparticles fuels at different BMEPs [31].

5. CONCLUSION

At the end of our review of the influence of nanoadditives on the performance and emissions of diesel engine, we have concluded the Nanoparticles used in fuel additives have a high surface area-to-volume ratio, allowing a larger contact area for fuel particles to interact with air molecules. Proper atomization and enhanced evaporation rates have been observed due to the better mixing of fuel particles and air, resulting in a more efficient combustion.

Metal oxide-based nonadditive provides oxygen for CO oxidation and also absorbs oxygen for the decrease of NOx. Furthermore, using metal oxide nanoparticles with higher oxygen content has been found to result in a reduction in exhaust emissions along with an improvement in engine performance. Metal-based additives can lead to a reduction in emissions by generating reactive hydroxyl radicals by reacting with water vapor in the exhaust, which break down harmful pollutants. Carbon-based nanoparticles have been used as an environmentally friendly additive in fuels used in diesel engines due to their non-metallic composition. CNTs enhanced engine performance and decreased emissions by shortening the ignition delay, increasing the evaporation rate of water particles, and increasing heat transfer during combustion, which further enhanced engine performance and reduced emissions. GO nanoparticles are particularly useful in reducing CO emissions due to their larger chemical reactivity, which promotes combustion. However, GO may increase NOx emission caused by the increased cylinder pressure and temperature.

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