ORIGINAL RESEARCH (AR)

DOI: 10.4274/jems.2022.65882

Journal of ETA Maritime Science 2022;10(3):145-155

Investigation of the Effect of CeO_2 Nanoparticle Addition in Diesel Fuel on Engine Performance and Emissions

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Abstract

In this study, the effects of the additive on engine performance and emissions were investigated by adding cerium oxide (CeO_2) nanoparticles (NPs) into diesel fuel. The use of CeO_2 NPs as an additive increased the lower calorific value (LHV) of the fuel while decreasing its viscosity and density. As a result of the experiments, an increase of 8.99% in engine torque was obtained in DCe100 fuel which 100 ppm CeO_2 NPs were added compared to diesel (D0) fuel. The increase in the LHV had a positive effect on the specific fuel consumption. The use of CeO_2 NPs resulted in an increase in brake thermal efficiency (BTE) due to the increased ending temperature of combustion. A 5.44% increase was obtained in DCe100 fuel compared to D0 fuel in terms of BTE. With an increase in the amount of CeO_2, carbon dioxide (CO), hydrocarbon (HC), and smoke emissions were reduced. Compared to D0 fuel, the lowest values were obtained with the DCe100 fuel. CO emissions were reduced by 18.27%, HC emissions by 30.12%, and soot emissions by 21.63%. However, nitrogen oxides (NO_x) emissions increased with rising CeO_2 amount and in-cylinder temperature. The highest NO_x value in DCe100 fuel was obtained with an increase of 6.65% compared to D0 fuel.

Keywords: CeO_2, Engine performance, Exhaust gas emissions, Nanoparticle additives

1. Introduction

The importance of energy is increasing with the increase in population growth and the acceleration of urban and industrial transformation. The world economy is fragile due to the finite and diminishing fossil fuel reserves, which play a crucial role in meeting the demand for energy [1]. Approximately 95% of the transportation sector uses fossil fuels, which corresponds to half of the global oil consumption [2]. Diesel engines are mostly preferred in transportation due to their high brake thermal efficiency (BTE), long life, and high engine power (EP). But the use of fossil fuels causes the formation of harmful emissions. Many countries and organizations are putting pressure on companies to reduce emissions and design more environmentally friendly engines to limit these emissions [3,4]. Previous studies aimed to provide suitable combustion conditions in diesel engines to raise engine performance and reduce harmful exhaust emissions. It is difficult to achieve through only engine design studies [5]. The quality of the combustion process determines the performance of internal combustion engines, including torque, fuel economy, and toxic emissions. Fuel cannot be fully utilized under lean combustion, resulting in reduced output power, and increased specific fuel consumption (SFC) and toxic emissions. Enhancing the spray evaporation properties of liquid fuels is the major key to improving engine combustion [6]. Emissions are directly related to the quality, properties, and combustion characteristics of the fuel. The most crucial fuel property which affects the combustion of diesel fuel is the cetane number (CN) of fuels. Furthermore, physical peculiarities of the fuel, such as viscosity and density, also affect combustion. There are numerous applications for improving the chemical and physical properties of fuel [7]. NPs additive is one of them [8], which can be directly mixed with the fuel and used without making any changes in the engine, increasing the quality of diesel fuel and improving combustion. With the improved combustion, there are decreases in exhaust emissions [9].

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Received: 03.02.2022
Accepted: 26.07.2022

To cite this article: A.B. Arslan and M. Çelik, "Investigation of the Effect of CeO2 Nanoparticle Addition in Diesel Fuel on Engine Performance and Emissions. *Journal of ETA Maritime Science*, vol. 10(3), pp. 145-155, 2022.

Adding NPs to diesel fuel enhances the thermo-physical characteristic of the fuel, including catalytic activity, thermal conductivity, surface-to-volume ratio, mass distribution, self-ignition temperature, CN, and LHV [8,10,11]. Because of the very small size of the NPs fuel additives, it is simple to manipulate the chemical and physical properties of the fuel. NPs additives containing iron, boron, and aluminum atoms show effects such as longer flame duration and reducing ID time during combustion [12]. CeO_2 NPs have unique properties such as high thermal stability, absorbing UV rays, electrical conductivity, high hardness, specific chemical reactivity, high oxygen retention, and carrying capacity. Due to these features, it has a wide range of applications, including glass polishing, automotive, corrosion inhibitor for metals, light-sensitive material protective additive, oxidation catalyst, and solar panels, as well as its low production cost [13,14].

CeO_2 NPs added to the fuel affect viscosity and ignition temperature [15]. Saraee et al. [16] conducted experiments by mixing the CeO_2 NPs additive into diesel fuel at 10, 20, and 40 ppm ratios. As a result of the experiments, the lowest level of 20 ppm in SFC was 0.27 kg/kWh. The lowest hydrocarbon (HC) emission was obtained at the rate of 40 ppm [16]. Selvan et al. [17] used 25 ppm CeO_2 NPs additive and 10% biodiesel and 20% ethanol additives in a water-cooled diesel engine. The lowest SFC was obtained in the mixture of CeO_2 and diesel at 0.3586 kg/kWh due to improved combustion by CeO_2. The addition of CeO_2 reduced CO emissions compared to diesel. The oxygen contribution of cerium causes a decrease in HC emissions after better completion of combustion. Adding NPs additives causes a slight increase in nitrogen oxide (NOx) emissions, increasing the combustion temperature [17]. Sajeevan and Sajith [18] added 5, 15, 25, 35, and 40 ppm CeO_2 NPs additives to diesel fuel and used it in a 4-stroke water-cooled engine. They obtained an increase in the flash point when the CeO_2 concentration was increased. It was stated that the BTE increased by 6% with the addition of 35 ppm CeO_2 in fuel. The efficiency started decreasing when the additive ratio was more than 35 ppm due to the oxygen support provided by CeO_2, leading to improved combustion. A decrease was obtained in HC emissions as the CeO_2 concentration was increased [18]. In his experiments, Aalam [19] used 25 and 50 ppm CeO_2 NPs additives in a single cylinder diesel engine. It was detected that the mixture gives better results than diesel in BTE. The highest BTE was obtained in 50 ppm additive ratio as 25.9% at full load. SFC decreased by 9% when the additive ratio was 50 ppm. The addition of the additive caused an increase in NOx emissions. Smoke and CO emissions were reduced by 36% and 26%, respectively, at full load and 50 ppm CeO_2 [19]. Dinesha et al. [20] used 10, 30, and 80 nm CeO_2 NPs on a mixture of 20% biodiesel and 80% diesel. The highest in-cylinder pressure value was obtained at 30 nm. It was stated that the mixed NPs improved the combustion while reducing the ID and SFC. There was a 35% reduction in HC emissions when 30 nm NPs were added to the mixture. They observed that adding CeO_2 to the mixture acts as a catalyst, lowering the temperature of the carbon activity and CO emissions. Thus, the oxidation of CO produces CO_2 when the temperature drops [20]. Muruganantham et al. [21] added 25, 50, and 75 ppm CeO_2 NPs into corn oil methyl ester-diesel fuel mixture (B10). They stated that the physicochemical features of the fuel were enhanced with the addition of CeO_2 NPs. Thus, the authors determined the optimum NPs ratio as 50 ppm during the experiment. BTE was 34.42% in B10 fuel and 34.7% after 50 ppm nanoparticle addition. The SFC obtained decreased by 3.96% with 50 ppm CeO_2 NPs additive compared to B10 fuel. At 50 ppm CeO_2, hydrocarbon emissions decreased by 13.63%, carbon monoxide (CO) emissions by 16.6%, while NOx emissions increased by 6.15% when compared to B10 fuel [21]. Nayak et al. [22] added aluminum oxide, zinc oxide, and graphene NPs in waste cooking oil biodiesel to improve engine performance. After determining the optimum biodiesel ratio, they mixed diesel fuel with a 20% biodiesel ratio and added NPs. According to the authors, all NPs reduced HC and CO emissions. Furthermore, they stated that an increase in BTE was observed with the addition of NPs. The authors stated that due to the higher surface volume ratio of NPs, the BTE increased as they provided higher EP resulting in a higher heat transfer rate in biodiesel blends. Conversely, compared to diesel, biodiesel and NPs mixtures reduce HC and CO emissions because they provide better combustion due to the higher oxygen content [22]. Mohan and Dinesha [23] found in their study that hydrogen peroxide (H_2O_2) concentrations at different rates (0.5%, 1%, and 1.5%) and amounts (40 and 80 ppm) of CeO_2 NPs with a 20% biodiesel-80% diesel content. They aimed to evaluate the combined effect of adding a fuel mixture on diesel engine performance and exhaust emissions [23]. Ağbulut et al. [24] synthesized graphene oxide (GO) NPs and added different amounts (100, 500, and 1000 ppm) to waste cooking oil (WCO)/diesel fuel mixtures containing edible oil methyl ester (WCO) at different rates (0 and 15%). They assessed these mixtures in diesel engines and investigated their effects on combustion, performance, and emission. The experiments were carried out at a constant speed of 2400 rpm and different engine loads (3, 6, 9, and 12 Nm). The authors stated that GO NPs increase the oxygen ratio in the cylinder and accelerate the chemical reactions until the combustion process, thus providing complete combustion. For this reason, they stated that CO emissions decreased by 22.5% and HC emissions by 30.23%. Furthermore, NOx emissions decreased by 15,17% due to the superior surface/volume ratio and thermal features of GO NPs. The authors reported that the energy content of the test fuels improved, and therefore BTE increased by 7.90%, while brake SFC (BSFC) decreased by 9.72% with the addition of GO NPs. Thus, GO NPs could offer a satisfactory solution to improve the deteriorating properties caused by biodiesel and diesel mixtures in diesel engines [24]. Vedagiri et al. [25] investigated the performance, combustion, and emission parameters of a DI engine powered by grape seed oil biodiesel besides the addition of nano-cerium oxide and zinc oxide NPs. There was a 3.3% decrease in BTE of grape seed oil biodiesel than diesel because of the high viscosity of grape seed oil biodiesel fuel. Conversely, adding NPs improves the combustion process due to the oxygen content, reducing the fuel evaporation time and ID; thus increasing from 28.8% to 30.2% with the CeO_2 mixture and from 28.8% to 30.51% with the zinc oxide mixture. The authors reported that CO and HC emissions were reduced because CeO_2 and zinc oxide NPs act as oxidation catalysts, accelerating and improving combustion. They stated that CeO_2 and zinc oxide NPs significantly reduce NOx emissions and that grape seed oil biodiesel is an effective alternative fuel for diesel engines without any engine modification [25]. In general, the development and different uses of nanotechnology cause inevitable interactions between the environment and nanomaterials. According to the outcomes of previous studies, NPs have a positive impact on the performance of different chemical systems, but the release of metallic oxide NPs into the environment has raised many concerns [26].

This study presents the experimental results of the effect of CeO_2 NPs additive in diesel fuel to improve engine parameters without modifying the engine. Our additive ratios were higher when compared to similar studies. We hope this experimental study will be useful in determining different additive ratios. Furthermore, the study can be improved by using different fluid fuels with the same NPs.

2. Materials and Methods

In the experimental studies, the 4-stroke single cylinder Antor 3LD510 diesel engine, the technical specifications of which are given in Table 1, and the Net Brake engine dynamometer were used as the engine loading equipment. During the experiments, a load cell was used with a precision of 1 g and a measuring range of 0-50 kg for the motor loading. Calibration settings were made according to the instructions received from the manufacturer. The measuring range of the dynamometer used in the experiments is 0-5000 rpm, and the torque of the engine measurement range is 0-350 Nm. During this experimental test process, Bosch-BEA 350 model device (Table 2) was used for measuring exhaust emissions, and the Bosch-BEA 070 model device (Table 3) was used for smoke emission measurement. CeO_2 additive, which has a purity level of 99.98%, was provided by Ege NanoTek for this study. Figure 1 shows the ultrasonic mixer. CeO_2 additive was incorporated into the diesel fuel using an ultrasonic mixer in the amounts of 25 ppm, 50 ppm, 75 ppm, and 100 ppm for 45 min at 50 °C. The test setup consists of two basic measurement systems. The engine test system measures engine torque, SFC, exhaust gas temperature (EGT), and engine oil temperature, and the emission measurement system analyzes exhaust gas. Figure 2 depicts the prepared test setup schematically, and Table 4 presents the features of test fuels [27]. The accuracy and uncertainty values of the parameters obtained as a result of the experiments are given in Table 5. The properties of the CeO_2 additive used in the experiments are shown in Table 6.

Table 1. *Technical specifications of the test engine*

Specifications	
Brand	Antor 3LD510
Engine Type	CI
Number of cylinders	1
Cylinder diameter (mm)	85
Stroke (mm)	90
Stroke volume (cm^3)	510
Compression ratio	17.5:1
Maximum engine speed (rpm)	3000
Maximum power (kW)	12 (3000 rpm)
Maximum torque (Nm)	32.8 (1800 rpm)

Table 2. *Technical specifications of Bosch-BEA 350*

	Measuring Range	Sensibility
CO	0-10% vol	0.001% vol
HC	0-9999 ppm	1 ppm
NO	0-5000 ppm	<=1 ppm
CO_2	0-18% vol	0.01% vol
O_2	0-22% vol	0.01% vol

Table 3. *Technical specifications of Bosch-BEA 70*

	Opacity	k value
Measurement range	0-%100	0.1%
Absorption coefficient (k)	0-9.99 m^{-1}	0.01 m^{-1}
Designation	Worth	
Measuring chamber length	215 mm	
Area of application	+5 °C–+40 °C	
Relative humidity of the ambient air	<%90	

2.1. CeO_2 Nanoparticles

The addition of NPs as an additive to fuel has proven to be a promising technology to improve diesel performance and reduce exhaust emissions. Due to its proven thermo-physical properties, researchers are interested in NPs to analyze properties such as BTE, engine performance, fuel efficiency, carbon emission, and smoke emissions [28]. The thermal conductivity of the fuel can be improved due to the large surface-to-volume ratio and micro-size of the CeO_2 NPs. The boiling point of the fuels is decreased after

Figure 1. *Ultrasonic mixer*

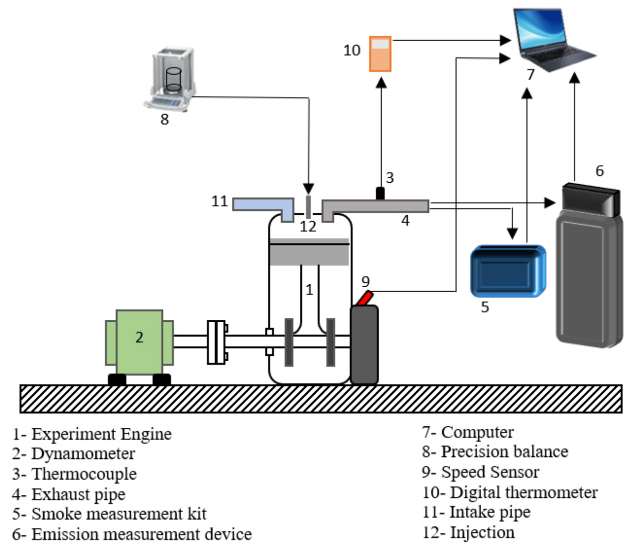

Figure 2. *Schematic view of the experimental system*

Table 6. *Features of the nanoparticle*

Powder size	20 nm
Purity	99.995%
Surface area	20-50 m^2/g
Density (Bulk)	0.8-1.1 g/cm^3
Density (True)	7.132 g/cm^3

Table 4. *Features of the test fuels*

Fuels	Kinematic viscosity (mm^2/s 40 °C)	Flash point (°C)	Density (kg/m^3 15 °C)	Calorific value (MJ/kg)
	ASTM D 445	ASTM D 93	ASTM D 4052	ASTM D 2015
D0	2.60	67	0.860	39.81
DCe25	2.52	64	0.846	40.02
DCe50	2.44	62	0.838	40.10
DCe75	2.39	59	0.834	40.14
DCe100	2.32	57	0.829	40.22

Table 5. *Features of the test fuels*

Parameters	Accuracy (±)	Uncertainty (%)
Temperature (°C)	±1 (°C)	±0.1
Time (s)	±0.1 s	±0.4
Load (N)	±1 N	±0.25
Engine speed (rpm)	±10 rpm	±0.2
Fuel (g)	±0.1 g	±0.1
Exhaust gas temperature (°C)	±1 (°C)	±0.1
Encoder (°CA)	±1°	±0.3
Cylinder pressure transducer (bar)	±0.1 bar	±0.1
Specific fuel consumption (g/kWh)	---	±0.94
Brake thermal efficiency (%)	---	±0.76

adding the NPs. At the high temperature inside the cylinder, NPs form layers when the fuel droplets overheat and swell. After all, a severe vaporizing event named micro explosions occurs (Figure 3).

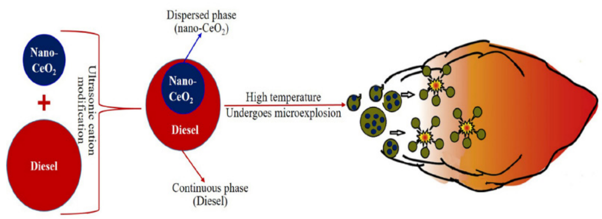

Figure 3. *Micro explosions and secondary atomization of NPs added fuels [29]*

NPs: Nanoparticles

CeO_2 NPs can store oxygen molecules in oxygen-rich conditions. It can form an oxygen buffer by releasing this stored oxygen when they reach the oxygen-poor region. The improvement of oxidation ensures more oxygen reaches fuel molecules, improves combustion, and provides a decrease, especially in PM emissions. Furthermore, the presence of Ce molecules in combustion can reduce the energy required for the combination of H and C atoms, affecting the emission changes positively. Researchers showed that the size of CeO_2 NPs affects the in-cylinder temperature during combustion. NPs can be a heat sink source during fuel combustion, trapping heat and lowering temperatures inside the combustion chamber (Figure 4).

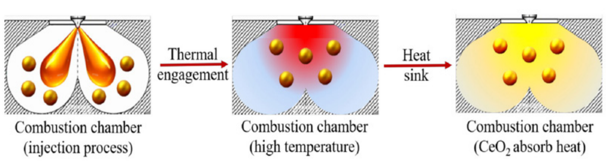

Figure 4. *Thermal activity of NPs [29]*

NPs: Nanoparticles

The evaporation process of nanofluid droplets is too complex for interactions between the surfaces of NPs. Furthermore, collisions accelerate the formation of nucleation sites for random movement of NPs [30]. Since the ambient temperature is much higher than the boiling point of diesel, the CeO_2 NPs are heated faster by thermal radiation than the fuel droplet. When the nanofluid droplet gets heated by the temperature of ambience, it moves and collides with NPs by generating the heat surrounding oil and forming small bubbles on the surface. A few heterogeneous nucleation sites are also formed inside droplets. Droplets burst into large bubbles, the large droplet shrinks, and most droplets are evaporated directly by microburst (Figure 5) [31]. It can also extend droplet life by preventing strong micro-explosion events that can occur during evaporation. The intensity of secondary atomization is affected by the thermo-physical properties of the base fuel and the stability of NPs, as well as the density, porosity, and structure of the nanofluid [32].

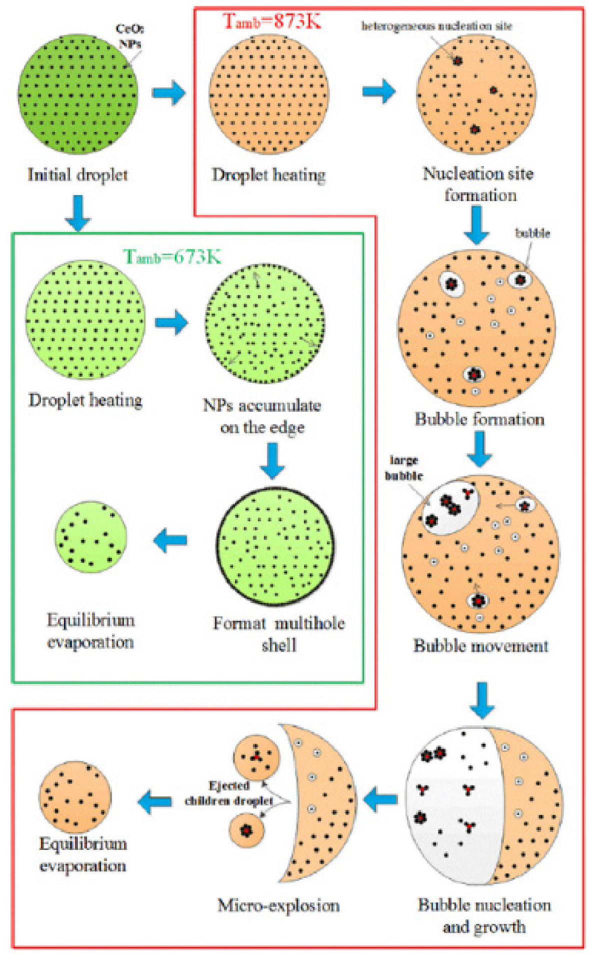

Figure 5. *Evaporation mechanism of nanofluid fuel droplets [31]*

3. Results

3.1. Engine Torque

Figure 6 presents the effect of CeO_2 NPs mixed with diesel fuel on engine torque. Maximum engine torque was achieved at 1800 rpm. While 25.68 Nm torque was obtained in D0 fuel, it was observed that the engine torque increased as CeO_2 concentration increased. Torque increase was 3.89%, 4.67%, 6.81, and 8.99% for DCe25, DCe50, DCe75 and DCe100 fuel mixtures, respectively at 1800 rpm. The increase in maximum engine torque was 13.91% for the DCe100 mixture at 2000 rpm. Using of CeO_2 additive

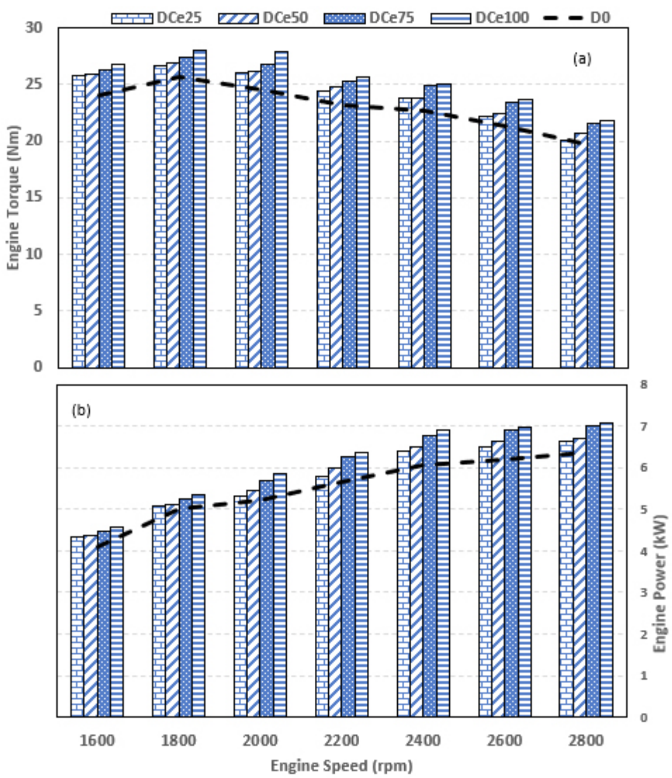

Figure 6. *Alteration of engine torque (a) and EP (b) with respect to engine speed*

EP: Engine power

provides better combustion by enhancing the air/fuel mixture in the cylinder, resulting in better torque. Due to the presence of oxygens in the additive, fuel molecules could access more oxygen, completing combustion and resulting in higher engine torque [12,18,33].

3.2. Engine Power

Figure 6 shows the effect of CeO_2 NPs addition into diesel fuel on EP. The power increases as the CeO_2 concentration rise and maximum power was achieved at 2800 rpm. While the EP was 6.35 kW in diesel fuel, the maximum increment in EP was 11.58% with the addition of 100 ppm CeO_2 compared to diesel fuel. According to diesel fuel, the increase in EP was 4.27, 5.45, and 10.16% in DCe25, DCe50, and DCe75 fuel mixtures, respectively. The highest power increase was obtained as 13.57% in addition to 100 ppm CeO_2 at 2400 rpm fuel. The lower viscosity of the fuel resulted in a higher microburst rate [31]. Adding CeO_2 to diesel fuel reduced the viscosity and density of fuels while increasing LHV. This allows the fuel to have better air/fuel mixtures and better atomization properties in the cylinder. Increased quality of the combustion affects power directly [34-37]. A high surface volume ratio provides better oxidation of fuel mixtures. Thus, high combustion enthalpy and energy density can be released to increase the maximum power [38].

3.3. Specific Fuel Consumption

BSFC is a vital parameter for engine performance because it gives information about how efficiently the amount of fuel supplied to the engine is converted into work [39]. Figure 7 depicts the effect of CeO_2 NPs addition to diesel fuel on the SFC. The lowest SFC was obtained at 1800 rpm, where the maximum torque was obtained. While diesel fuel yielded 330.68 g/kWh, it was 322.64, 316.87, 313.49, and 310.50 g/kWh for DCe25, DCe50, DCe75, and DCe100 fuels with CeO_2 added, respectively. The maximum reduction rate in SFC was obtained at 2000 rpm with 7.69% in DCe100 fuel compared to D0 fuel. Adding CeO_2 NPs additive to diesel fuel increases the LHV and thus provides a reduction in SFC. Adding CeO_2 to the fuel increases the surface/volume ratio [37,40]. The microburst properties of CeO_2 addition positively affected the SFC [41], which depends on density, viscosity, and LHV of the fuel used. Fuels with higher "lower calorific value" are known to have lower consumption [42].

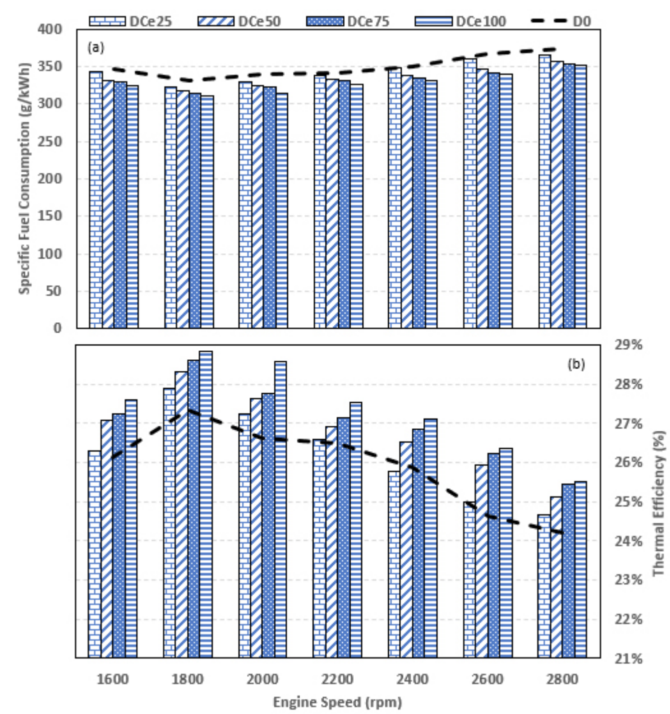

Figure 7. *Alteration of SFC (a) and BTE (b) with engine speed*

SFC: Specific fuel consumption, BTE: Brake thermal efficiency

3.4. Brake Thermal Efficiency

The addition of NPs to diesel fuel increases LHV, improving combustion by increasing the evaporation rate of the fuel

[37,43]. Figure 7 depicts the effect of CeO_2 NPs additive on BTE. The highest BTE was obtained as 28.83% in DCe100 fuel at 1800 rpm. While it was 27.34% in D0 fuel, with the increase in CeO_2 concentration, an increase of 1.97%, 3.63%, 4.64%, and 5.44% was obtained in DCe25, DCe50, DCe75, and DCe100 fuels, respectively. The highest increase rate was 7.25% in DCe100 fuel at 2000 rpm. The decrease in viscosity with the addition of NPs improves the chemical reaction and minor fuel droplets, providing a more extensive active surface and contact area. The chemical reactivity of the fuel increases with the presence of reactive surfaces, which may result in better combustion, and thus BTE goes higher [9,37,44,45]. Considering the effects of fuel properties, lower viscosity and density facilitate evaporation of the fuel in the cylinder. However, mixing fuel droplets with ambient air positively affects the evaporation properties of fuel mixtures. The sprayed fuel droplet is smaller due to the lower viscosity and consequent lower surface tension. Better atomization quality can promote the mixing of fuel and air and provide a full combustion environment to reduce emissions by increasing the BTE of a diesel engine [46].

3.5. Exhaust Gas Temperature

EGT is affected by engine load, amount of fuel taken into combustion chambers, and ID. The LHV of the burned fuel is also effective on the EGT [47]. While the EGT temperature was 575 °C in D0 fuel at 1800 rpm, where the maximum torque was obtained. It was 593 °C in DCe100 fuel. EGT goes up with increasing engine speed and CeO_2 concentration. The highest EGT was obtained as 741 °C at 2800 rpm in DCe100 fuel, and it was 710 °C in DCe0. The addition of CeO_2 NPs to the fuel increases the LHV and the temperature of the EGT by rising the heat produced in each unit mass. Also, the oxygen content of NPs additive enhances combustion in cylinders and increases EGT [48].

3.6. Carbon Dioxide Emissions

Figure 8 presents the effects of CeO_2 addition to diesel fuel on CO emissions. CO emissions indicate insufficient combustion of the fuel. The main factors for the formation of CO emission are a heterogeneous mixture, insufficient O_2 availability, and fewer residence time for combustion [49]. The causes of CO emissions are a lack of oxygen in the fuel and incomplete combustion. CO emissions are primarily controlled by the air/fuel ratio in engines. The concentration of CO emissions in the exhaust increase in the case of a rich mixture of air/fuel ratio in cylinders [7,12]. The lowest CO was obtained in DCe100 fuel at 2800 rpm. Compared to D0 fuel at 2800 rpm, reductions in CO emissions of DCe25, DCe50, DCe75, and DCe100 fuels were respectively 5.12, 10.25, 15.70, and 18.27%. CeO_2 added to the fuel showed a catalyst effect, improved combustion, and provided oxygen support. This way, CO molecules react more with oxygen and turn into CO_2 molecules. Boost oxygen concentrations in combustion chambers ensure that CO emission is more dispersed and meets with more oxygen [9,50]. Increases in temperature in the cylinder with the addition of NPs additives provide better fuel burning, leading to reductions in CO emissions [51].

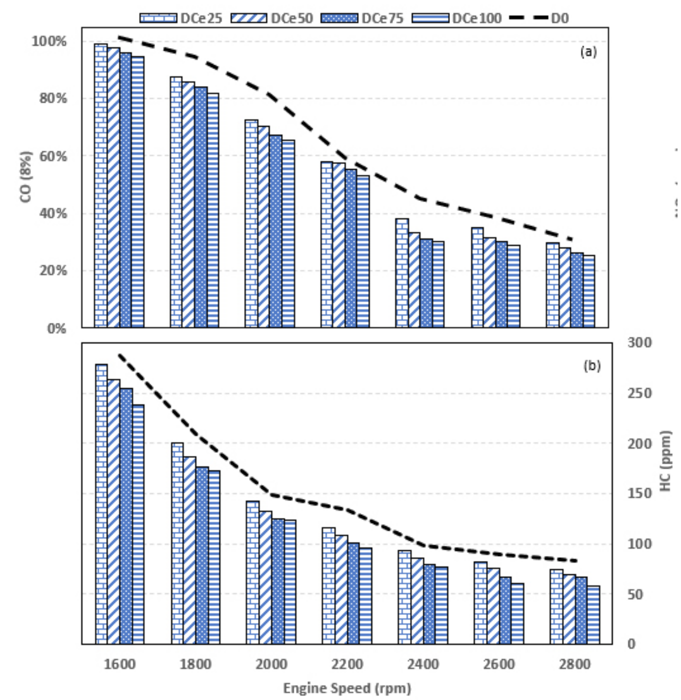

Figure 8. *Alteration of CO emissions (a) and HC emissions (b) according to engine speed*

CO: Carbon dioxide, H: Hydrocarbon, NOx: Nitrogen oxides

3.7. Hydrocarbon Emissions

Figure 8 presents the effects of incorporating CeO_2 NPs into diesel fuel on HC emissions. While HC emission was 209 ppm in D0 fuel at 1800 rpm, where the engine torque was maximum, it was 200, 187, 177, and 173 ppm in DCe25, DCe50, DCe75, and DCe100 fuels, respectively. HC emission decreased with increasing CeO_2 concentration and engine speed. Minimum HC emission was obtained at 2800 rpm. At 2800 rpm, DCe25, DCe50, DCe75 and DCe100 fuels with CeO_2 NPs additive reduced HC emissions by 9.64%, 16.87%, 19.27%, and 30.12%, respectively when compared to D0 fuel. The highest reduction rate in HC emissions was 33.3% in DCe100 fuel at 2600 rpm. The addition of CeO_2 provided better combustion, increased the oxygen content, and improved combustion quality. As a result, the combustion was completed, and HC emissions were reduced [52].

3.8. NOx Emissions

Figure 9 shows the effect of adding CeO_2 NPs to diesel fuel on NOx emissions. The lowest NOx amount was obtained as 977 ppm in D0 fuel at 1600 rpm. At low engine speeds, NOx emissions are lower due to the low temperature of inside cylinders. As engine speed and CeO_2 concentration increase, NOx emissions increase. Compared to diesel fuel NOx emissions increased in DCe25, DCe50, DCe75, and DCe100 fuels 1.23%, 5.43%, 9.21%, and 12.28%, respectively at 1600 rpm. The NOx emission increase in DCe100 fuel was 8.19% at 1800 rpm. Maximum engine torque was obtained as 6.65% at 2800 rpm for the maximum EP. The main reason for NOx formation is the increased combustion temperature in the cylinder. It mostly consists of nitrogen molecules in the intake air into the cylinder. If the temperature in the combustion chamber exceeds 1800 °C, oxygen and nitrogen molecules decompose and form NO emissions depending on temperatures [47,53,54]. Mixing NPs with diesel raises the flame temperature, causing more N_2 to oxidize to NOx in the atmospheric air during combustion. Therefore, NOx emissions for NPs blended fuels are higher than pure diesel under all test conditions [55]. One of the reasons for the increase in NOx emissions is the rapid combustion process affects combustion temperature. Since the addition of CeO_2 NPs to diesel fuel increase the LHV of the fuel, the combustion end temperature increase. The oxygen in CeO_2 and the high reaction rate cause an increase in the temperature of inside cylinders and NOx formation [48,56]. Also, the rising of BTE triggers NOx emissions [57].

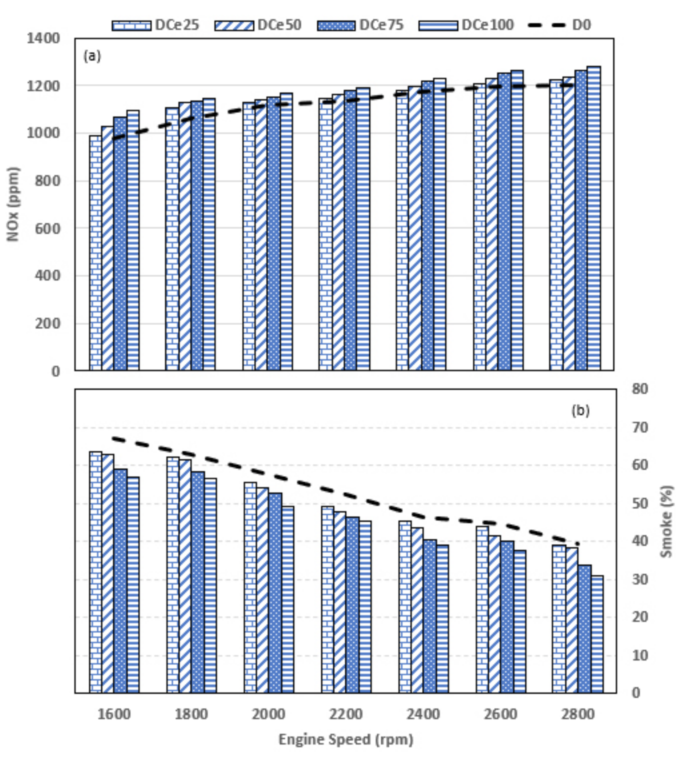

Figure 9. *Alteration of NOX emissions (a) and smoke emissions (b) according to engine speed*

NOx: Nitrogen oxides

3.9. Smoke Emissions

Smoke emission occurs in the rich fuel zones in the cylinders during combustions. The particles of the emission are solid carbon molecules. These molecules are formed when they cannot reach oxygen in the fuel-rich regions in the combustion chamber [47,58]. The effect of CeO_2 addition to diesel fuel on smoke emissions is shown in Figure 9. As the amount of CeO_2 increases, the amount of smoke emission decreases. While it was 62.7% in D0 fuel at 1800 rpm, the reduction in smoke emission was 9.88% in DCe100 fuel compared to D0 fuel. The minimum amount of smoke emissions was measured using DCe100 fuel at 2800 rpm. The reduction in smoke emissions in DCe25, DCe50, DCe75, and DCe100 fuels was 1.27%, 3.05%, 13.99%, and 21.63%, respectively. Smoke emissions can be reduced using the oxygen provided by CeO_2. Furthermore, lowering viscosity and density improves fuel and air mixture recovery and lowers smoke emissions [59,60].

4. Conclusion

The density and viscosity of diesel fuels were decreased by CeO_2 NPs additives. This study improved LHV, resulting in a better air/fuel mixture. The inclusion of CeO_2 NPs additive in diesel fuel provided more oxygen to reach the fuel particles in combustion. Thus, more efficient combustion was formed by nano additive. The CeO_2 NPs created a higher contact area with the fuel droplets. It was observed that the increased active surface area provided an improvement in combustion reactions.

The addition of CeO_2 NPs additive to diesel fuel positively affected emissions. A better combustion occurred due to the oxygen provided by CeO_2, and the rate of unburned fuel was reduced. As an outcome, combustion temperatures in the cylinders increased, and the nitrogen molecules taken from the air reacted more with the oxygen. As a result, while CO, HC, and smoke emissions decreased, NOx emissions increased.

According to the results, the present research positively impacts the fuel industry. However, the long-term impact on the environment and human health due to adding NPs to liquid fuel and subsequent combustion is unknown. Because of their high chemical activity, NPs can pass through cell walls and skin. As a result of combustion, particles coming out from the exhaust mix with water and soil and eventually cause poisoning [61-63]. However, strict laws regarding exhaust emissions exist in Europe to prevent them from contributing to global warming. Due to the negative effects of NPs on human health and the environment, new laws and rules regarding exhaust NPs from exhaust pipes are required before commercialization.

Acknowledgments

This study was produced on the basis of the master thesis prepared by the first author under the supervision of the second author. Abdullah Burak Arslan took part in performing the experiments, analyzing the data, creating the graphs, interpreting the results and writing the article. Mehmet Çelik took part in performing experiments, analyzing the data, interpreting the results and writing the article.

Authorship Contributions

Concept design: A.B. Arslan, M. Çelik, Data Collection or Processing: A.B. Arslan, M. Çelik, Analysis or Interpretation: A.B. Arslan, M. Çelik, Literature Review: A.B. Arslan, Writing, Reviewing and Editing: A.B. Arslan, M. Çelik.

Funding: The author(s) received no financial support for the research, authorship, and/or publication of this article.

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