JISSE
ISSN: 2636-4425
Journal of International Society for Science and Engineering
Vol. 3 No. 2, 29-35 (2021)
JISSE
E-ISSN:2682-3438

Enhancement of diesel engine performance and emissions burning biodiesel with cerium oxide nanoparticles additive

Ahmed M. Hussien[1], M. S. Gad[2], Bahaa M. Kamel[3,*], Ahmed S. Abdallah[4],Mohamed S. Shiba[5]

[1]Mechanical Engineering Department, Higher Technological Institute, 6th of October City Branch, Giza, Egypt
[2]Mechanical Engineering Department, Faculty of Engineering, Fayoum University, Egypt
[3]Mechanical Engineering Department, National Research Centre, 12622 Giza,
[4]Faculty of Engineering (Mataria), Helwan University, Cairo, Egypt
[5]Automotive Engineering Department, Higher Technological Institute, 6th of October City Branch, Giza, Egypt

ARTICLE INFO

Article history:
Received: 23/03/2021
Accepted: 2021-06-01
Online: 2021-06-01

Keywords:
Waste cooking oil
Biodiesel
Cerium oxide
Engine Performance
Emissions

ABSTRACT

This work is oriented to enhance the diesel engine emissions and performance run with biodiesel from waste cooking oil (WCO) blended with nano cerium oxide. Methyl ester properties were confirmed with ASTM standards. Biodiesel blends were achieved by mixing of 10 and 20% by volume of methyl ester to pure diesel as B10 and B20, respectively. Concentration of 50 ppm nano CeO2 was blended with biodiesel blends as B10C50 and B20C50. The maximum enhancements in thermal efficiencies of B10C50 and B20C50 were 5 and 10 %, respectively about B10 and B20. The highest increases in brake power of blended nano additive were 7.5 and 11% biodiesel were about B10 and B20, respectively. The highest decreases in specific fuel consumptions were 6 and 11%, respectively about biodiesel blends for addition of nano additive. Methyl ester mixtures with nano material achieved the highest declines in CO concentrations by 17 and 22%, respectively related to B10 and B20. The maximum decreases in NOx emissions were 8 and 13% for B10C50 and B20C50, respectively about biodiesel blends. Biodiesel mixture B20 with CeO2 nano additive of 50 ppm concentration was recommended to show the emissions reductions and performance improvement about methyl ester blends.

1. Introduction

Traditional fuels are well known for its harmful emissions, moreover the increasing energy consumption and fossil fuel supplies, all these factors led to find out the alternatives of conventional fuels. Biodiesel is directly used in conventional diesel engine, so it is renewable alternative replacement of diesel oil [1]. NOx, HC, and CO emissions were reduced with the addition of CeO2 additive [2]. Influence of cerium oxide nano material in water emulsified diesel-cotton oil biodiesel blend on engine combustion was considered. Biodiesel blend B10W3CeO290 shows the best performance and less emission about all fuels [3, 4]. Nanofluids enhance the combustion characteristics and thermophysical properties of base fuels. Nano materials are classified as non-metallic, metallic, and organic in the base fuel. There are improvements in heat transfer, surface to volume ratio and thermal conductivity about base fuel [5, 6]. Nanomaterials have excellent properties as an additive to improve the diesel engine combustion characteristics [7]. Combustion of diesel engine using nano CeO2 additive in blends of ethanol, diesel and methyl ester was investigated. Cerium oxide nanoparticles of 25, 50, 100 ppm were used. Cerium oxide is a catalyst used for the nitrogen and carbon dioxide reductions because of the oxidation. The carbon deposits were eliminated at the cylinder wall due to the burn off and activation energy of nano particles and this leads to the decreases of smoke and hydrocarbon emissions [8].

* Bahaa M. Kamel, Mechanical Engineering Department, National Research Centre, Giza, Egyt, +201227004606, bahaa2004eg@yahoo.com

Waste cooking and tyre pyrolysis oils blends were used by the inclusion of nano additive cerium oxide of 100 mg per liter of fuel for the improvement of emissions and performance. Thermal efficiency of 80% WCO and 20% tyre oil resulted in the enhancement of 25.62% at full load but the specific fuel consumption was increased by 23.68% about crude diesel. The decreases in CO and HC emissions were 95 ad 91.96%, respectively and the increase in NOx emission was 5.84% for WME80TPO20CeO2100 about diesel fuel [9]. Engine tests were performed at different engine loads using 5% biodiesel with water emulsification of 3, 5 and 7% by weight mixed with nano cerium oxide of 90 ppm. Methyl ester mixture B5 of 3% water and 90 ppm cerium oxide can be used as a substitute to diesel oil led to the engine improvement and less emissions [10, 11]. Evaporation characteristics of diesel oil and nano CeO2 of 1.25% were investigated at temperature range from 673 K to 873 K. Nanofluid and diesel fuels have the same evaporation characterization at low temperatures but evaporated faster at high temperatures. The droplets of ceria nanoparticles have greater attraction and less surface tension. Nanofluid droplets have the less the energy to achieve micro explosion and leads to the shorter time of evaporation. The smaller droplet volume consumes the shorter heat transfer time [12].

Nano cerium oxide of 25 and 50 nm concentrations were added to diesel oil. Addition of CeO2 nano powder improves the fuel spray and leads to the combustion acceleration. Blending with nano CeO2 produces the decreases in CO, HC and NOx emissions about diesel oil. Particle size of 50 nm cerium oxide leads to the less HC and CO emissions about base fuel. The smaller size of cerium oxide nano particles has the higher surface area and reaction rate due to the smaller size which has the easily aggregation of fuel molecules [13]. Emissions and combustion of diesel engine using CeO2 nano particle and 20% of hydrogen were studied. Addition of nanoparticles has not any influence on the physicochemical properties of blends. Blending of nano cerium oxide produces the improvement in thermal efficiency of 4.3% at full load. Inclusion of CeO2 leads to the less carbon deposits and NOx emission due to the oxidation [14]. Nano additive was diffused at different concentrations of 250, 500 and 750 mg/1. The thermal efficiency was improved by 8% by inclusion of nano CeO2 and exhaust emissions were reduced about base fuel. Inclusion of nano material leads to the combustion start advancing and evaporation improvement. Inclusion of 500 mg/l of CeO2 nanoparticles enhanced the engine combustion characteristics due to the oxygen content which produces the catalytic reactivity to improve the combustion [15]. Addition of nano cerium oxide improves the reaction rate and ignition characteristics because of the larger surface area. Inclusion of nano CeO2 produces the activated free radicals as O, OH and H which enhances the burning rate [16].

Cerium oxide nano additive was blended with Lemongrass oil emulsion fuel in diesel engine. Thermal efficiency was enhanced due to the enhancement in combustion characteristics and the high surface area / volume ratio compared to base fuel. The reductions in CO and HC emissions were 15.69 and 35.5% compared to without additive, respectively. The secondary atomization and micro-explosion of ceria nanoparticles improve the evaporation, ignition characteristics and reaction rate [17]. Blends of biodiesel B5, cerium oxide nano material of 90 ppm and water of 2%, 4% and 6% by weight have the influence on performance and emissions compared to diesel oil. The metal-based additive enhances the thermal efficiency because of the catalytic activity [18, 19]. Nano cerium oxide reduces the fuel activation energy and eliminates the soot production in the early stage of combustion [20]. Effect of CeO2 nanoparticle mixed with methyl ester on emissions and diesel engine performance was described. Thermal efficiency was increased by the nanomaterial additive addition and less HC, NOx and CO emissions were shown due to the oxygen content [21].

Blending cerium oxide of 20 ppm with watermelon seed oil leads to the decline of CO and NOx emissions about diesel oil [22]. Impact of cerium oxide nano additive blended with Citrus Medica Peel oil biodiesel on engine combustion was investigated. Specific fuel consumption was declined by 10.59% due to the enrichment of nano additive about base fuel. There were reductions in NOx and CO emissions by ceria addition [23]. WCO methyl ester and diesel oil mixing of 20, 40 and 60% by volume with cerium oxide nanoparticles on diesel engine combustion characteristics was studied. Thermal efficiency of diesel engine used diesel, B20C30, B40C30 and B60C30 were 24.6, 25.17, 26.95 and 27% but specific fuel consumption values were 0.38, 0.37, 0.35 and 0, 0.33 kg/kWh, respectively [24]. Influence of CeO2 nano particle of 20 ppm concentration blended with Grape seed oil on emissions and performance of diesel engine was investigated. CO emission was decreased about diesel oil under the impact of nano additive inclusion. Nano cerium oxide of 150 ppm concentration has the less NOx emission about base fuel [25, 26].

Neochloris oleoabundans algae oil biodiesel of 20% by volume was mixed with CeO2 nanoparticle of 25, 50, 75 and 100 ppm. Thermal efficiency was increased but and the exhaust emissions were decreased under the nano material impact [27]. The emissions reductions were higher under the dosing level of 40 ppm. Smoke and HC were decreased but NOx emission was increased. The optimum level of nano cerium oxide of 40 ppm leads to the engine performance improvement [28]. Nano CeO2 was included to Jatropha biodiesel at concentrations of 10, 30 and 60 ppm. The decreases in smoke, HC, CO and NOx concentrations were 32, 33, 60 and 13%, respectively by nano additive addition [29]. There were reductions in HC, NOx and CO emissions as 23.46, 6.57 and 18.27%, respectively by using CeO2 of 100 ppm [30]. Tyre oil blends of 5, 10, 15 and 20% were added to nano cerium oxide of 50 and 100 ppm. Biodiesel blend B5 with nano additive of 100 ppm leads to the highest thermal efficiency, higher NOX and lower smoke emissions [31]. WCO B20 was blended with nano CeO2. The maximum increase in thermal efficiency was 2.5% but the highest decreases in smoke, NOx and HC emissions were 14, 23 and 20%, respectively at injection pressure of 240 bar under the inclusion of cerium oxide nanoparticles [32].

Literature focused on the effect of nano CeO2 mixed with WCO biodiesel on diesel engine emissions and performance. However, little studies shed the light on the impact of fixed nanoparticle concentration blended with different biodiesel blends on the engine performance and emissions. Inclusion of nano materials led to the enhancement in the thermal properties of fuel, complete combustion, and improper fuel- air mixing. Lower biodiesel percentages were used as B10 and B20 which have the lower problems in viscosity, atomization and spray of fuel compared to diesel oil. Also, the work focused on the application of nano cerium oxide of smaller size of 50 nm which enhances the nano material dispersion and stability in base fuel. Waste cooking oil disposal has the harmful effects on the environment and water sources. Methyl ester was derived from economical and non-edible WCO feedstock. Biodiesel blends properties were measured and confirmed with ASTM standards and near to rude diesel. Nano materials were included to methyl ester mixtures B10 and B20 at constant concentrations of 50 ppm. Performance parameters such as brake power, specific fuel consumption and thermal efficiency were shown. CO and NOx emissions were evaluated. Comparative study was displayed to show the effect of B10C50 and B20C50 on engine performance and emissions compared to crude diesel and biodiesel blends.

2. Materials and methods

2.1. WCO Biodiesel production process

Restaurants, hotels, and manufacturers provided the waste cooking oil feedstock. Impurities were removed from the oil after it was purified. To minimize the moisture, the oil was preheated to 90°C. The oil was mixed with methanol at a molar ratio of 6:1 using a NaOH catalyst, and the mixture was continuously stirred at temperature of 70°C. To complete the transesterification, the mixture was allowed to settle in a separating funnel under the gravity for 24 hours, as shown in Fig.1. To remove the unreacted methoxide, the glycerol was removed, and the oil methyl ester was washed with water. Methyl ester was heated to eliminate the water traces [33-35]. Diesel oil was blended with WCO biodiesel in volume ratio of 10 and 20% as B10 and B20, respectively. The methyl ester blends physical and chemical properties are illustrated in Table 1. The methyl ester lower calorific value is lower than that of pure diesel. Biodiesel has the higher flash point and cetane number than crude diesel.

2.2 Preparation of biodiesel nano blends

Nano cerium oxide (CeO2) particles were provided from Nanotech Egypt with its specifications as indicated in Table 2. In the central laboratories of National Research Centre, Egypt, Transmission Electron Microscope (TEM) (Model: JOEL JEM-2100) was used to characterize the surface and morphological structure of ceria. The images of nanoparticles collected using transmission electron microscope (TEM) are shown in Figure 2. The nano additives were diffused in the base fuel using ultrasonication and magnetic stirring. The uniform distribution was achieved by constant agitation in 30 minutes time. Concentration of 50 ppm, 0.05 g of CeO2 nanoparticle was applied to one liter of biodiesel blend named as B10C50 and B20C50. Calorific values of biodiesel blends B10 and B20 were

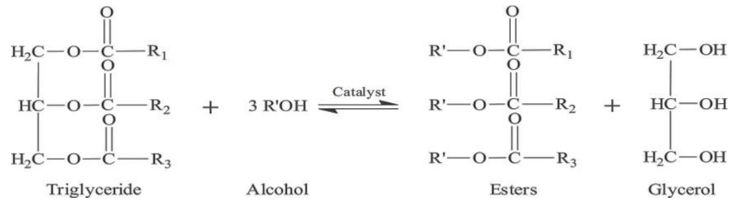
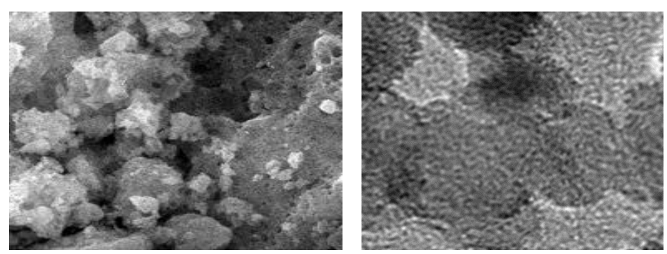


Figure 1: Transesterification process

decreased by 1 and 1.5% in comparison to diesel fuel. Inclusion of nano cerium oxide to B10 and B20 blends contributed to the heating value increases of 2 and 1% compared to methyl ester mixtures B10 and B20 and this leads to the improvements in output power and performance parameters. The density values of B10 and B20 were increased compared to diesel oil by 9%, respectively. Addition of nano CeO2 leads to the increases of densities up to 1.5 and 3%, respectively about B10 and B20. Viscosities were increased for all methyl ester mixture about diesel oil. The increases in viscosities of B10 and B20 blends about diesel oil were 9 and 11%, respectively. Addition of nano CeO2 increased the viscosity up to 20 and 30% for B10 and B20 blends, respectively as compared to B10 and B20. These increases in viscosity of nano fuels were insignificant. Flash point of B10C50 and B20C50 were increased about biodiesel blends B10 and B20 by 5 and 2.5%, respectively. High flash point ensures that the fuel cannot ignite accidentally when exposed to an open flame, which leads to the higher safety during the fuel transportation and storage. Properties of tested fuels are shown in Table 2.



(a)SEM **(b) TEM**

Figure2: SEM and TEM photos of nano cerium oxide.

Table 1: Properties of WCO biodiesel with nano additives

Properties	Method	Diesel oil	B100	B10	B20	B10C50	B20C50
Density at 15.56 kg/m^3	ASTM D-4052	817	892	827	836	835	839
Kinematic Viscosity at 40°C, centi poise	ASTM D-445	3.92	5.15	4.29	4.7	4.5	4.8
Flash Point, °C	ASTM D-93	53	108	60	73	64	76
Calorific Value, MJ/ kg	ASTM D-224	42.2	39.5	41.7	41.5	41.8	41.6

Table 2: Nano particles properties

Form	**Nano powder**
Particle size	**<50 nm (BET)**
Density	**7.13 g/ml at 25°C**
Bulk density	**0.53 g/ml at 25°C**
Linear formula	**CeO_2**
Molecular weight	**172.11**
Smiles string	**O=[Ce]=O**
Inchi	**1S/Ce.2O**
Melting point	**2400 ℃**
Inchi key	**CETPSERCERDGAM-UHFFFAOYSA-N**
Boiling point	**3500 ℃**

2.3 Experimental set up

The experiments were carried out using a four-cylinder, four-stroke diesel engine with a maximum output power of 85 hp. The specifications of the used test engine were mentioned in Table 3. Figure 3 depicted the schematic representation of the setup method. The engine brake output was measured using an eddy current dynamometer that was directly connected to the test engine with a maximum output power of 150 kW. The specifications of dynamometer were shown in Table 4. Fuel tanks of diesel, biodiesel blend and nano additive blended were supported at the engine test rig. One burette with stopcock was used for the fuel flow rate measurements. Exhaust gases such as NOx and CO were evaluated. A gas analyzer (model MRU DELTA 1600-V, O2 (0-22%) electrochemical cell, CO2 (0-10%) NDIR bench, HC (0-2000 ppm) NDIR bench, NO (0-4000 ppm) electrochemical cell, and NO2 (0-1000 ppm) electrochemical cell) was used. During the experiments, the engine speed ranged from 800 to 2400 rpm. NOx, CO emissions and thermal efficiency have the highest uncertainties of 0.5, 0.5 and 1%, respectively. Brake power, specific fuel consumption, and engine speed have the maximum uncertainties of 1.5, 1 and 1 %, respectively. The total uncertainty was determined by adding the uncertainties of the parameters as follows:

$$\sqrt{(ubp)^2+(usfc)^2+(uN)^2+(uther)^2+(uCO)^2+(uNOx)^2}$$
$$=\sqrt{(1.5)^2+(1)^2+(1)^2+(0.5)^2+(0.5)^2}=\pm 2.17\%$$

Where:

ubp: brake power uncertainty
uN: Engine speed uncertainty.
uCO: CO emission uncertainty
usfc: uncertainty of specific fuel consumption
uther: Thermal efficiency uncertainty
uNOx: uncertainty of NOx emission

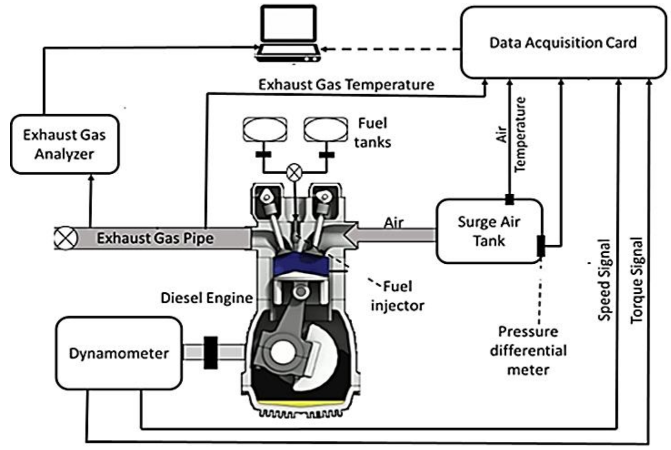


Figure 3: Experimental setup schematic diagram

Table 3: Engine specifications

	Value
Model	**Cummins 4BT3.3-C85 Diesel engine**
Compression ratio	**18.3:1**
Capacity	**3.3 L**
Max. power	**85 hp at 2600 rpm**
Max. torque	**291 N.m at1600 rpm**

Table 4: Dynamometer specifications

Parameters	**specifications**
Dynamometer type	**SE150 Model**
Maximum torque and power	**500 N.m, and 150 kW**
Maximum outlet water temperature	**60 ºC**
Weight	**560 kg**
Maximum voltage and current	**250 VAC and 5 A**
Pulse pick up	**Inductive**
Load cell	**Strain gauge full bridge**
Energizing coil voltage	**90 V**
Input resistance	**375 ohms**
Sensitivity and excitation	**2.7 MV/V and 10 VDC**
Overall size (length x width x height)	**632 x 470 x 689 mm**

3. Results and discussions

3.1Engine brake power

Figure 4 shows the effect of methyl ester blends with nano cerium oxide inclusion of 50 ppm on brake output power. The increase in brake power with the increased engine speed is due to the increased fuel consumption. Biodiesel blends have the lower output power than crude diesel because the methyl ester has the lower calorific value than diesel oil. Biodiesel fuel has the higher viscosity and density, which causes the atomization, spray problems and lower brake power than diesel oil. Inclusion of nano additive to biodiesel resulted in the increases in brake power about biodiesel blends because of the improper fuel- air mixing, improved combustion, and enhanced atomization. The oxygen content, catalytic reactivity, higher surface area / volume ratio and improved thermal characteristics produced the improvements of brake power about base fuels. Brake power achieved the maximum enhancements for B10C50 and B20C50 about 7.5 and 11%, respectively compared to methyl ester mixtures B10 and B20. These findings were agreed with the literature [4, 7, 8, 11].

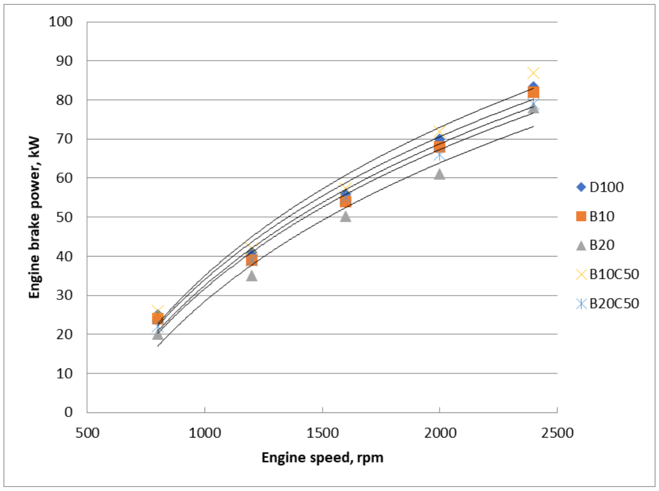


Figure 4: Brake power of biodiesel blends blended with nano CeO2 with the engine speed variation

3.2 Specific fuel consumption (SFC)

Figure 5 indicates the influence of methyl ester blend with nano cerium oxide inclusion of 50 ppm on SFC. Owing to the increase of injected fuel, specific fuel consumption values decrease as the engine speed increases until it reaches to the engine speed of 2000 rpm for all fuels. Since biodiesel has a lower calorific value than diesel oil, specific fuel consumptions of methyl ester mixtures were higher than crude diesel. Biodiesel fuel has the higher viscosity and density, which causes the vaporization, spray and atomization problems than diesel oil. Because of the enhanced fuel-air mixing and atomization, inclusion of nano additive to methyl ester resulted in the lower specific fuel consumption about biodiesel mixtures. The catalytic surface reactivity, oxygen content, improved thermal properties and higher surface area to volume ratio resulted in the reductions of SFC about base fuels. SFC achieved the maximum decreases for B10C50 and B20C50 about 6 and 11%, respectively about methyl ester blends B10 and B20. These results were confirmed with the literature [7, 8].

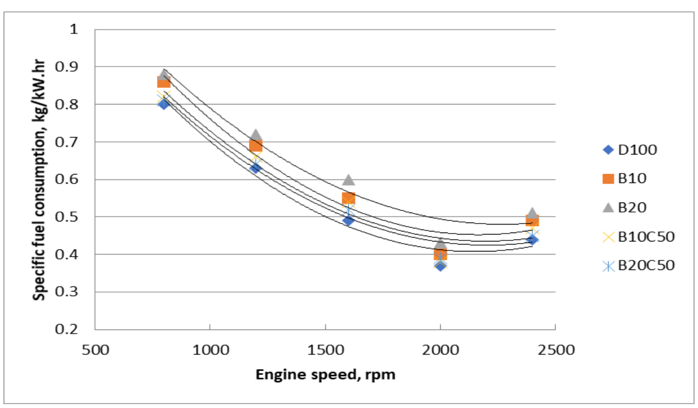


Figure 5: SFC values at different engine speeds for nano fuel blends

3.3 Thermal efficiency (TE)

Influence of WCO methyl ester mixtures with the inclusion of cerium oxide nano additive on thermal efficiency was shown in Fig. 6. Because of the increased consumption of fuel, the increase of thermal efficiency was associated with the increase of engine speed until it reached to the engine speed of 2000 rpm. Owing to the lower calorific value and higher viscosity of methyl ester compared to pure diesel, the thermal efficiencies of WCO biodiesel mixtures were lower than crude diesel. Improper fuel-air mixture, atomization and vaporization problems of biodiesel blends were shown. The heat produced by the evaporation of nano additives mixed with methyl ester mixtures improved the fuel-air mixing, heat transfer, and catalytic activity. The addition of nano particles resulted in the reduction of vaporization time and the thermal conductivity increase. The oxygen content leads to the complete combustion and the increase of TE. The highest improvements in thermal efficiencies for biodiesel mixtures B10 and B20 with CeO2 nano additive of 50 ppm concentration were 5 and 10%, respectively about biodiesel blends, respectively. These findings were confirmed with the literature [14, 17, 23].

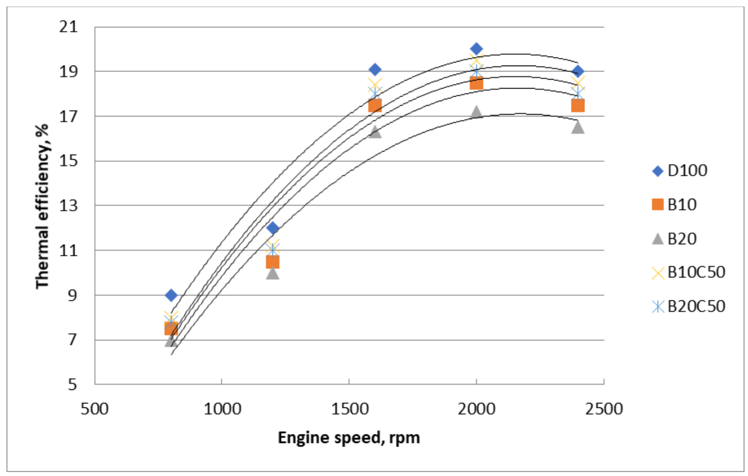


Figure 6: Effect of nano additive on thermal efficiency with the variation in engine speed

3.4 CO emissions

Figure 7 shows the CO emissions values for WCO biodiesel blends with CeO2 nanoparticles. With the increase in engine speed, the fuel consumption and rich air-fuel mixture increase, resulting in the increase of CO emissions. The presence of oxygen in methyl ester mixtures allowed for the complete combustion and the reduction of CO emissions as compared to diesel oil. Catalytic reactivity and larger surface contact area about the base fuels were shown. Improved thermal properties, fuel-air mixing and ignition improvements lead to the reduction of CO emission under the effect of nano additive. The combustion efficiency was improved due to the improved heat transfer, evaporation rate, and thermal conductivity. In contrast to methyl ester blends, the overall reductions in CO emissions for B10C50 and B20C50 were 17 and 22 %, respectively. Other researchers [14, 23] have observed the same pattern of nanoparticle addition.

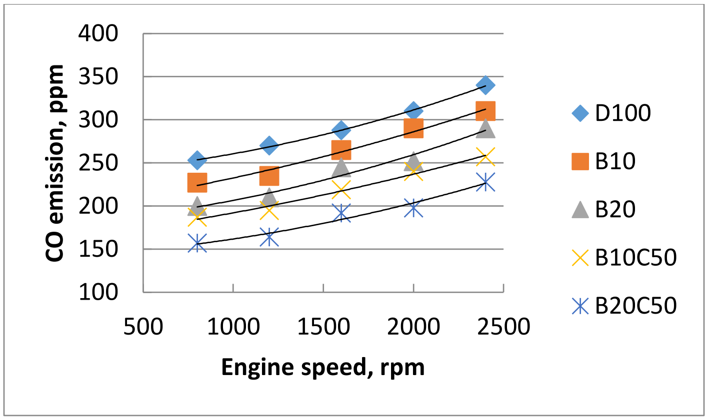


Figure 7: Impact of nano CeO2 additives on CO emission at different engine speeds

3.5 NOx emissions

Inclusion of nano cerium oxide in methyl ester blends B10 andB20 on NOx emissions is illustrated in Fig.8. NOx emission is influenced by the adiabatic flame and cylinder temperatures. Because of the increased fuel consumption, the increase in engine speed results in the increase in NOx emissions. The increased NOx emissions of methyl ester mixtures B10 and B20 about diesel oil were caused by the oxygen content. Higher cylinder temperature for biodiesel mixtures lead to the production of thermal NOx. The reduction in NOx emissions in methyl ester mixtures with nano material dose of 50 ppm was demonstrated. The addition of nano additives enhanced the fuel atomization, vaporization and the increase rate of heat transfer. NOx emissions are reduced as the evaporation rate and combustion process enhancement about base fuel. Larger surface area and catalytic reactivity for biodiesel blends with nano material about the base fuels were shown. In blended methyl ester with ceria, the highest reductions in NOx emissions were 8 and 13 %, respectively, for biodiesel blends B10 and B20. The NOx emission pattern is in line with the literature [14, 21, 23].

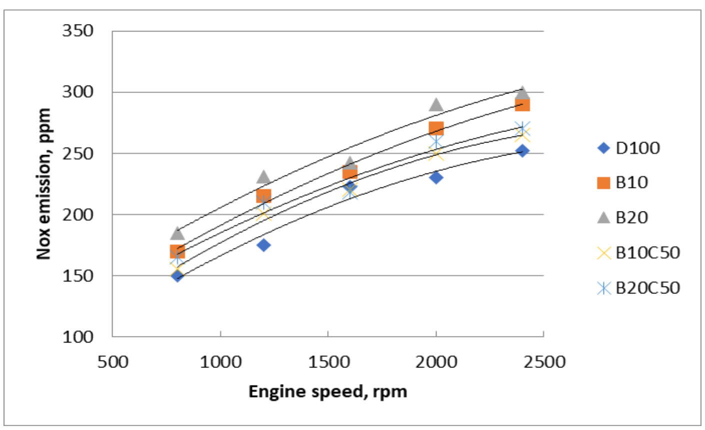


Figure 8:NOx emissions values for nano additives at the engine speed variation

Conclusions

This paper discusses the emissions and performance of WCO biodiesel blended with CeO2 nanomaterial in a diesel engine. Transesterification was used to manufacture methyl ester from waste cooking oil. As B10 and B20, WCO methyl ester was blended with crude diesel in volume percentages of 10% and 20%, respectively. As B10C50 and B20C50, nano cerium oxide was applied to biodiesel blends B10 and B20 at concentrations of 50 ppm. The important conclusions are summarized as:

- The ASTM requirements were met by the properties of waste cooking biodiesel as compared to diesel oil.
- The maximum improvements in brake power of B10C50 and B20C50 were 7.5 and 11% compared to biodiesel blends B10 and B20, respectively due to the improvements in lower heating values of biodiesel blends with nano additive.
- As compared to biodiesel blends B10 and B20, the highest thermal efficiency increases of methyl ester with nano materials were 5 and 10%, respectively, but the greatest decreases in SFC values were 6 and 11%, respectively because of the improved combustion, heat transfer and thermal properties.
- In contrast to methyl ester blends, its blends with nano cerium oxide additive at dose of 50 ppm achieved the maximum reductions in CO emissions of 17 and 22 %, but the highest reductions in NOx emissions were 8 and 13 %, respectively due to the improvements in surface contact area, thermal properties, and uniform fuel- air mixing.
- Mixing of WCO biodiesel mixtures B10 and B20 with ceria at concentration of 50 ppm is recommended to enhance the performance and reduce the emissions methyl ester mixtures.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] M. S. Gad, B.M. Kamel, I.A. Badruddin, Improving the diesel engine performance, emissions and combustion characteristics using biodiesel with carbon nanomaterials, Fuel 2021; 288: 119665.

[2] Chandran, M., R. Chinnappan, and C.K. Ang, Effect of nano cerium oxide additive with tire oil blends on diesel engine combustion and emissions parameters with soot morphology analysis. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2020: p. 1-13.

[3] Vellaiyan, S., Effect of cerium oxide nanoadditive on the working characteristics of water emulsified biodiesel fueled diesel engine: An experimental study. Thermal Science, 2020. 24(1 Part A): p. 231-241.

[4] Samuel, N. and M. Shefeek, Performance, and emission characteristics of a CI engine with cerium oxide nanoparticles as additive to diesel. International Journal of Science and Research, 2015. 4(7): p. 672-676.

[5] V. Saxena, N. Kumar, V. K. Saxena, A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled C.I. engine, Renewable and Sustainable Energy Reviews 2017; 70: 563–588.

[6] V. W. Khond, V.M. Kriplani, Effect of nanofluid additives on performances and emissions of emulsified diesel and biodiesel fueled stationary CI engine: A comprehensive review, Renewable and Sustainable Energy Reviews 2016; 59: 1338–1348.

[7] T. Kegl, A. K. Kralj, B. Kegl, M. Kegl, Nanomaterials as fuel additives in diesel engines: A review of current state, opportunities, and challenges, Progress in Energy and Combustion Science 2021; 83: 100897.

[8] V. AM. Selvan, R.B. Anand, M. Udayakumar, Effect of Cerium Oxide Nanoparticles and Carbon Nanotubes as fuel-borne additives in Diesterol blends on the performance, combustion and emission characteristics of a variable compression ratio engine, Fuel 2014;130: 160–167.

[9] G. Sujesh, S. Ganesan, S. Ramesh, Effect of CeO2nano powder as additive in WME-TPO blend to control toxic emissions from a light-duty diesel engine – An experimental study, Fuel 2020; 278: 118177.

[10] M. Aghbashloa, M. Tabatabaei, E. Khalife, B. Najafi, S. M. Mirsalim, A. Gharehghani, P. Mohammadi, A. Dadak, T. R. Shojaei, Z. Khounani, A novel emulsion fuel containing aqueous nano cerium oxide additive in diesel–biodiesel blends to improve diesel engines performance and reduce exhaust emissions: Part II – Exergetic analysis, Fuel 2017; 205: 262–271.

[11] E. Khalife, M. Tabatabaei, B. Najafi, S. M. Mirsalim, A. Gharehghani, P. Mohammadi, M. Aghbashlo, A. Ghaffari, Z. Khounani, T. R. Shojaei, M. A. M. Salleh, A novel emulsion fuel containing aqueous nano cerium oxide additive in diesel–biodiesel blends to improve diesel engines performance and reduce exhaust emissions: Part I – Experimental analysis, Fuel 2017; 207: 741–750.

[12] M. Dai, J. Wang, N. Wei, X. Wang, C. Xu, Experimental study on evaporation characteristics of diesel/cerium oxide nanofluid fuel droplets, Fuel 2019; 254: 115633.

[13] Z. Zhang, Y. Lu, Y. Wang, X. Yu, A. Smallbone, C. Dong, A. P. Roskilly, Comparative study of using multi-wall carbon nanotube and two different sizes of cerium oxide nanopowders as fuel additives under various diesel engine conditions, Fuel 2019; 256: 115904.

[14] S. Manigandan, R. Sarweswaran, P. B. Devi, Y. Sohret, A. Kondratiev, S. Venkatesh, M. R. Vimal, J. J. Joshua, Comparative study of nanoadditives TiO2, CNT, Al2O3, CuO and CeO2 on reduction of diesel engine emission operating on hydrogen fuel blends, Fuel 2020; 262: 116336.

[15] A. Murugesan, A. Avinash, E. J. Gunasekaran, A. Murugaganesan, Multivariate analysis of nano additives on biodiesel fuelled engine characteristics, Fuel 2020; 275: 117922.

[16] M. Hatami, M. Hasanpour, D. Jing, Recent developments of nanoparticles additives to the consumables liquids in internal combustion engines: Part I: Nano-fuels, Journal of Molecular Liquids 2020; 318: 114250.

[17] M. Annamalaia, B. Dhinesh, K. Nanthagopal, P. SivaramaKrishnan, J. I. JR. Lalvani, M. Parthasarathy, K. Annamalai, An assessment on performance, combustion and emission behavior of a diesel engine powered by ceria nanoparticle blended emulsified biofuel, Energy Conversion and Management 2016; 123: 372–380.

[18] Jiaqiang E, Z. Zhang, J. Chen, M. Pham, X. Zhao, Q. Peng, B. Zhang, Z. Yin, Performance and emission evaluation of a marine diesel engine fueled by water biodiesel-diesel emulsion blends with a fuel additive of a cerium oxide nanoparticle, Energy Conversion and Management 2018; 169: 194–205.

[19] A. Gharehghani, H. Pourrahmani, Performance evaluation of diesel engines (PEDE) for a diesel-biodiesel fueled CI engine using nano-particles additive, Energy Conversion and Management 2019; 198: 111921.

[20] J. Liu, J. Yang, P. Sun, Q. Ji, J. Meng, P. Wang, Experimental investigation of in-cylinder soot distribution and exhaust particle oxidation characteristics of a diesel engine with nano CeO2 catalytic fuel, Energy 2018; 161: 17-27.

[21] S. N. K. Reddy, M. M. Wani, Engine performance and emission studies by application of nanoparticles as additive in biodiesel diesel blends, Materials Today: Proceedings 2021, In press.

[22] V.S. Shaisundaram, M. Chandrasekaran, Investigation of watermelon seed oil biodiesel with Cerium oxide nanoparticle in CI engine, Materials Today: Proceedings 2021, In press.

[23] M. Shanmugama, S. Sathiyamurthy, G. Rajkumar, S. Saravanakumar, S. T. Prabakaran, V. S. Shaisundaram, Effect of thermal Barrier coating in CI engines fueled with Citrus Medica (Citron) peel oil biodiesel dosed with cerium oxide nanoparticle, Materials Today: Proceedings 2021; 37: 1943–1956.

[24] S. A. Ali, S. Hunagund, S. S. Hussain, A. H. Bagwan, The effect of nanoparticles dispersed in waste cooking oil (WCO) biodiesel on thermal performance characteristics of VCR engine, Materials Today: Proceedings 2021, In press.

[25] R. Sridhar, V.S. Shaisundaram, S. Baskar, S. Ramasubramanian, G. Sathiskumar, S. Sivabalan, Investigation of grape seed oil biodiesel with cerium oxide nanoparticle in CI engine, Materials Today: Proceedings 2021; 37: 1399–1402.

[26] CH.S. Harsha, Suganthan.T, S.Srihari, Performance and Emission Characteristics of Diesel Engine using Biodiesel-Diesel-Nanoparticle Blends- An Experimental Study, Materials Today: Proceedings 2020; 24: 1355–1364.

[27] K. Kalaimurugan, S. Karthikeyan, M. Periyasamy, G. Mahendran, Emission analysis of CI engine with CeO2nanoparticles added neochloris oleoabundans biodiesel-diesel fuel blends, Materials Today: Proceedings 2020; 33: 2877–2881.

[28] G. Vairamuthu, S. Sundarapandian, C. Kailasanathan, B. Thangagiri, Experimental investigation on the effects of cerium oxide nanoparticle on Calophyllum inophyllum (Punnai) biodiesel blended with diesel fuel in DI diesel engine modified by nozzle geometry, Journal of the Energy Institute 2016; 89: 668-682.

[29] A. Prabu, R.B. Anand, Emission control strategy by adding alumina and cerium oxide nano particle in biodiesel, Journal of the Energy Institute 2016; 89: 366-372.

[30] S. Akram, M. W. Mumtaz, M. Danish, H. Mukhtar, A. Irfan, S. Ali Raza, Z. Wang, M. Arshad, Impact of cerium oxide and cerium composite oxide as nano additives on the gaseous exhaust emission profile of waste cooking oil based biodiesel at full engine load conditions, Renewable Energy 2019; 143: 898-905.

[31] S.T. Kumaravel, A. Murugesan, C. Vijayakumar, M. Thenmozhi, Enhancing the fuel properties of tyre oil diesel blends by doping nano additives for green environments, Journal of Cleaner Production 2019; 240: 118128.

[32] S. Kumar, P. Dinesha, M. A. Rosen, Effect of injection pressure on the combustion, performance and emission characteristics of a biodiesel engine with cerium oxide nanoparticle additive, Energy 2019; 185: 1163-1173.

[33] B. Tesfa, R. Mishra, C. Zhang, F. Gu, A.D. Ball, Combustion and performance characteristics of CI (compression ignition) engine running with biodiesel, Energy; 51, pp. 101-115, 2013.

[34] J. Xue, T. E. Grift, A. C. Hansen, Effect of biodiesel on engine performances and emissions, Renewable and Sustainable Energy Reviews; 15, pp. 1098-1116, 2011.

[35] P. Tamilselvan,,N. Nallusamy, S. Rajkumar, A comprehensive review on performance, combustion and emission characteristics of biodiesel fuelled diesel engines, Renewable and Sustainable Energy Reviews; 79, pp. 1134-1159, 2017.

Abbreviation and symbols

ubp	brake power uncertainty
uN	Engine speed uncertainty
uCO	CO emission uncertainty
usfc	uncertainty of specific fuel consumption
uther	Thermal efficiency uncertainty
uNOx	uncertainty of NOx emission