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Experimental Investigation on the Effect of TiO_2 Nanoparticles Emulsion in Water on Emissions and Performance Characteristics of DI Diesel Engine

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Abstract: The world is presently confronted with the twin crisis of resource restriction and environmental degradation. The search for solutions that promise a harmonious correlation with sustainable development, energy conservation, efficiency, and environmental preservation has become highly important. The main purpose of innovative studies on fuel refinement and combustion engines is to improve fuel properties by adding fuel additives. In this study, the impact of Titanium dioxide, TiO_2, nanoparticles solution blended with diesel fuel on the performance and emission characteristics of four-stroke combustion engine OM 364 EU III, manufactured by IDEM Co and licensed by Daimler Benz, has been investigated. The selection of TiO_2 nanoparticles is based on the easy access in the market and the gap recognized; in previous literature, these nanoparticles were added to biodiesel or n-butanol blends. The proposed combined fuel in this study contains 2.5 ppm TiO_2 nanoparticles dissolved in 1200 [ml] water and added to 60 [Lit] base diesel fuel. The results of the aforementioned combined fuel have been compared with the base diesel fuel. It has been observed that applying nano-additives improves the mechanical performance of the diesel engine, such as power, torque, brake-specific fuel consumption, and thermal efficiency. Moreover, soot, unburned hydrocarbons, and carbon monoxide have declined by 2.78%, 3.55%, and 3.32%, respectively, due to TiO_2 nanoparticles' catalytic effect on fuel combustion. However, the amount of NOx has increased up to 3.09% because of the high cycle temperature.

Keywords: Titanium dioxide nanoparticles; Four-stroke combustion engine; Performance characteristics; Brake-specific fuel consumption; Emissions characteristics

1. Introduction

The world is presently confronted with the crisis of the resource restriction of petroleum fuels and the consequences of air pollution emergent from these fuels' combustion. Indiscriminate fuel depletion has resulted in a decline in underground-based carbon resources and environmental corruption. The search for promising fuels to create a harmonious correlation between energy conservation and environmental preservation has become highly significant, and it has led to investigations to improve fuel properties by adding fuel additives.

Several scientists and companies have studied the metal oxide nanoparticle additives in diesel fuel. Jung et al. [1] experimentally studied the effect of nano-additive on diesel-based fuels. Outcomes reveal that the thermal efficiency of the brake is improved, and the pollutants are reduced to an acceptable level. Low calorific value and high viscosity increase fuel consumption and the number of nitrogen oxides.

Scattergood [2] experimentally examined nano silicon/diesel, water, and nano aluminum/water, diesel reactions in an internal combustion engine. Results indicate that BSFC of nano silicon/diesel, water, and nano aluminum/water, diesel 21% and 37% decreased, and brake thermal efficiency, BTE, 16%, and 14% increased, respectively. Furthermore, NOx pollutants of diesel combustion in combination with water have diminished due to lower exhaust gas temperature. Nano-metal additives such as platinum-cerium, cerium-iron, manganese bromide, and copper have been used [3]. With the aim of pollutants reduction, alcoholic fuels in combination with gasoline fuel have been considered by Baby and Sundara [4]. Yang et al. [5] used a solution of 82.4% diesel and

5% water with 12.6% nano-organic additives. The outcomes reveal improved braking thermal efficiency, reduced combustion time, decreased pollutants, and enriched fuel consumption and combustion process. An experimental study on the effect of nano additives on combustion performance and pollution of diesel engines with biodiesel has done by Rashedul et al. [6]. Elfassakhany [7] found that the hybrid gasoline combination with n-butanol leads to declination of carbon monoxide, carbon dioxide, and unburned hydrocarbons in the gasoline engine. Selvan et al. [8] have used cerium nano oxides and carbon nanotubes in diesel, biodiesel, and ethanol fuels. They found that carbon nanotubes accelerate combustion and reduce ignition delays. Moreover, cerium oxide particles reduce carbon monoxide due to oxidation with carbon monoxide and decrease nitrogen oxides by absorbing oxygen. Also, the activation energy of cerium oxide burns carbon and hydrocarbon pollutants, and soot is highly reduced. Wagloehner et al. [9] investigated the oxidation of soot particles with oxygen in manganese oxides. The results show that soot reduced up to 80%. Mirzajanzadeh et al. [10] improve the performance characteristics of the diesel engine, such as power, torque, BSFC, and pollution characteristics like nitrogen oxides (NOx), carbon monoxide, hydrocarbons, and soot. For this purpose, different concentrations of nano-sodium solution with diesel-based fuel have been utilized. The results indicate that the nano catalytic oxidation reaction significantly improves the engine combustion performance and decreases all pollutants. Saraee et al. [11] experimentally and numerically considered diesel engine performance and exhaust emission with nanoparticles by an artificial neural network. They found that adding nanoparticles leads to the reduction of fuel consumption. Amirabedi et al. [12] found that to increase fuel productivity and reduce pollutants, metal nano-additives, oxygen additives, and antioxidants have been used to improve the cetane number. They improved the octane number in internal combustion engines by applying oxygen-containing nanoparticles such as alcohol, ether, and ester.

In recent years, TiO_2 nanoparticle has attracted the attention of researchers as a catalyst for blending with diesel and biodiesel fuels. The effects of various blends of TiO_2 nanoparticles on the performance, combustion, and emission characteristics of engines have been investigated. Örs et al. [13] probed the effect of TiO_2 nanoparticles as an additive in diesel/ biodiesel/ n-butanol blends. Parida et al. [14] investigated the effect of TiO_2 nano-additive on engines fueled with Karanja biodiesel blend. It was observed that the BTE and BSFC increase by 1.72% and 3.57%, respectively, compared to biodiesel blend. Dhahad et al. [15] studied the diesel fuel supplemented with nano-TiO_2 and nano-AL_2O_3. Sandhi et al. [16] evaluated TiO_2 nanoparticles as an additive in diesel- n-butanol - Bombax Ceiba biodiesel blends.

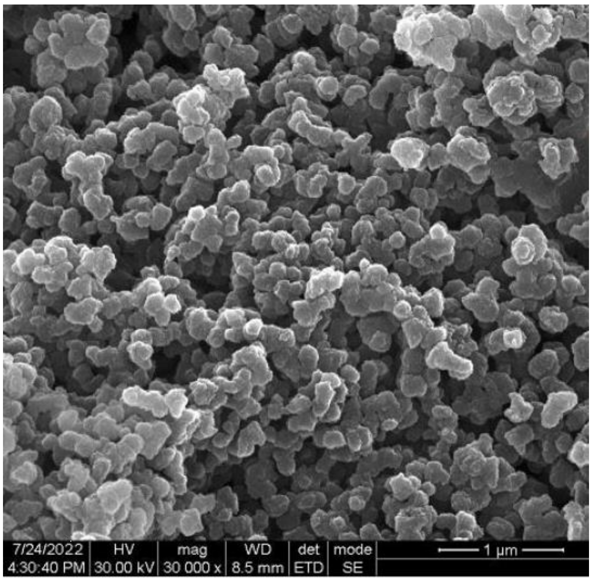
According to previous literature, these nanoparticles have been added to biodiesel or n-butanol blends. The major objective of this study is to evaluate the performance and emission characteristics of the DI engine with novel emulsion of 2.5 ppm TiO_2 nanoparticle additive for the first time. The proposed combined fuel is a blend of 120 [mg] TiO_2 nanoparticles dissolved in 1200 [ml] water and have been added to 60 [Lit] base diesel fuel. The results indicate an increase in the lighting point, viscosity, and density of the combined fuel in comparison to the base fuel. Moreover, the combined fuel has caused the 2.78%, 3.55%, and 3.32% reduction of soot, unburned hydrocarbons, and carbon monoxide, respectively, due to the improved combustion process and better atomization.

In this study, TiO_2 nanoparticles are applied as the additive to base gasoline fuel. For sediment prevention, 120 mg of TiO_2 nanoparticles are combined with 1200 ml of water and agitate in a magnetic stirrer for 30 minutes. Then the emulsion is placed in a 37 kHz ultrasonic bath for two hours at room temperature of 25℃ to ensure the homogeneity of the composition at a microscopic level. FEI Quanta 200 FEG MKII scanning electron microscope with a resolution of 1.2 nm is utilized to depict SEM images of TiO_2. According to Figure 1(a), TiO_2 nanofluid is clustered, roughly spherical, with a smooth surface and an average particle size of 35 nm. Figure 1(b) presents the obtained TiO_2 emulsion. Figure 2 bestow the magnetic stirrer and ultrasonic bath used in the tests. The combined fuel with TiO_2 nano-additives is compared with the base fuel in terms of lighting point, viscosity, heating value, and density and are listed in the Table 1.

A general view of the experimental setup is presented in Figure 3, consisting of the intercooler, air chamber, fuel tank, manometer, fuel metering unit, fuel flow meter, and indicators. A 400-kW eddy current dynamometer coupled to the test motor is used to measure engine power. The Load cell, temperature, pressure, and humidity sensors are mounted on it. Engine performance is evaluated by online engine performance analyzer software. The OM 364 LA diesel engine with turbocharger and intercooler is tested in this study, Figure 3. In the range of 1300-1800 RPM, this engine has a nominal power of about 100 kW and a maximum nominal torque of 430 N.m. The engine characteristics are fully presented in Table 2. Figure 4 shows a schematic view of this experimental study.

Table 1. Significant properties of fuels applied in this study

Feature	Unit	Combined Fuel	Base Fuel (Diesel)	Standard Test Method
Lighting point	℃	80	68	ASTM D-92
Viscosity	$mm^2/_S$	53.3	25.3	ASTM D-445
Calorific Value	$KJ/_{Kg}$	40101	42930	ASTM D-5865
Density	$Kg/_{m^3}$	910	830	ASTM D-4052



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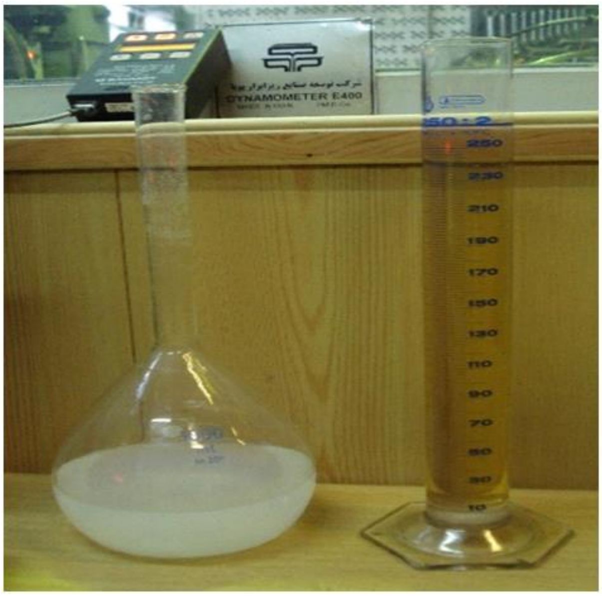


(b)

Figure 1. (a) SEM image of TiO_2; (b) The TiO_2 emulsion used in the tests

Figure 2. The magnetic stirrer and ultrasonic bath

According to the type of dynamometer used in this study, the European Stationary Cycle (ESC), which includes 13 modes at a constant speed, has been used to evaluate pollutants. For measuring emission concentration, an AVL gas analyzer is utilized. In the AVL gas analyzer, the storage temperature is between 0 to 45℃, the ambient temperature during operation is between 5 to 35℃, and the maximum relative humidity of the storage is 90%. The amount of soot, carbon monoxide, nitrogen oxides, unburned hydrocarbons, carbon dioxide, oxygen, and the actual air/fuel to stoichiometric ratio are measured.

The stability of the engine for achieving accurate results and letting different machine segments stabilize is essential. For this purpose, water and oil temperatures need to attain 90℃, the engine operating temperature. This condition is obtained by the engine running at 2600 engine speed for almost 10-15 min. The tests have been run at the full load of 1200 to 2600 engine speed with 200 RPM steps and partial loads ranging from 20 to 100 at full loads of 1500, 1800, and 2600 RPM.

Table 2. Technical specifications of the tested engine

Technical Specifications of the Tested Engine	
Model	OM 364 LA
Engine type	Diesel equipped with mechanical direct fuel injection system
Cylinders	4
Cylinder bore	97.5 mm
Stroke	133 mm
Emission standard	EURO3
Compression ratio	1: 2/17
valves	8
Total piston displacement	97/3Lit
Fuel type	Gasoline
Max output	128hp @ 2600 rpm
Max torque	430N.m @ 1300-1800 rpm

Figure 3. Diesel engine test cell view

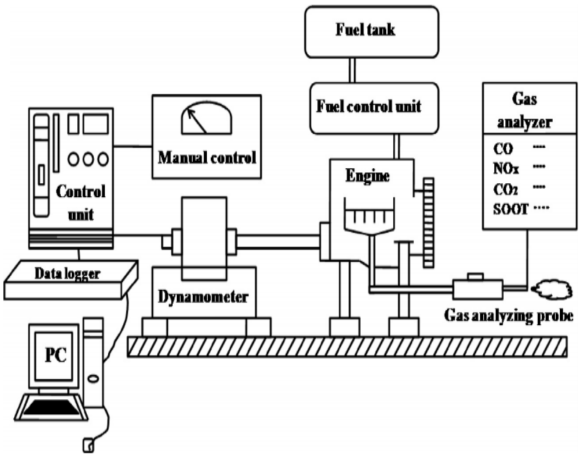


Figure 4. Schematic of diesel engine configuration

2. Environmental Impact of TiO_2 Nanoparticles

Titanium dioxide, TiO_2, has been industrially produced for over 100 years and used in various products like sunscreens and foods. Moreover, it is currently exploited as the most novel nanomaterial for mixing with diesel fuel due to its feature of containing a greater surface area to react with diesel molecules. In epidemiological studies, there are no specific effects related to cancer incidence of the TiO_2 nanoparticles. In FDA studies, TiO_2 nanoparticles are categorized as extremely low risk. The consensus of all studies is that small amounts represent a lower environmental risk, whereby the long-term effects of low doses of nano-TiO_2 remain unclear [17]. In this study, to minimize the proposed combined fuel effects on the environment a small dose of TiO_2, 2.5 ppm, was used.

3. Uncertainty Analysis

The experimental test has repeated four times, and 75% of the data has an error accuracy of less than 0.02. The most logical data having the lowest error rate has been selected. The uncertainty of this study has been considered as the standard deviation of the data set mean Eq. (1), [18].

$$W_R^+ = \left(\left(\frac{\partial R^+}{\partial X_1} W_1\right)^2 + \left(\frac{\partial R^+}{\partial X_2} W_2\right)^2 + \ldots + \left(\frac{\partial R^+}{\partial X_n} W_n\right)^2\right)^{1/2} \tag{1}$$

where, W_R^+, X_i, and W_i represents the overall uncertainty, the independent variable in the equation, and the uncertainty in that variable alone.

$$W_R^+ = [(\mu_{th})^2 + (\mathrm{BSFC})^2 + (\mathrm{Soot})^2 + (\mathrm{CO})^2 + (\mathrm{NOx})^2 + (\mathrm{T})^2 + (\mathrm{P})^2 + (\mathrm{RPM})^2]^{1/2} = 2.07 \tag{2}$$

Uncertainties in the parameters are presented in Table 3. The overall uncertainty of this study is 2.07, Which is in an acceptable range and can be inferred that the obtained results are reliable.

Table 3. Uncertainties in the parameters measured

Examined Parameters	% Uncertainty
μ_{th}	0.6
BSFC	0.4
Soot	1.2
CO	0.06
NOx	1.5
T	0.15
P	0.2
RPM	0.15

4. Results and Discussion

4.1 Brake Specific Fuel Consumption at Different RPMs

Brake Specific Fuel Consumption (BSFC) is one of the essential characteristics for comparing the engine in two various loads or two diverse fuels in the same load.

$$\mathrm{BSFC} = \mathring{m}_f / P \tag{3}$$

in which, $\mathring{m}_f$ $[g/h]$ is fuel consumption rate and P [KW] is brake power.

According to Figure 5, by increasing engine speed from 1200 to 1600 RPM with 200 RPM steps, the BSFC for both cases decreased. However, by increasing the engine speed from 1600 to 2600, the BSFC for both fuels increased. Besides, the combined fuel with TiO_2 nanoparticle has a lower BSFC. This decline in BSFC is for the explosion of the nanoparticle clusters in the fuel that causes the fuel droplets to become smaller and evaporate better in the combustion chamber, and result in improved combustion [16].

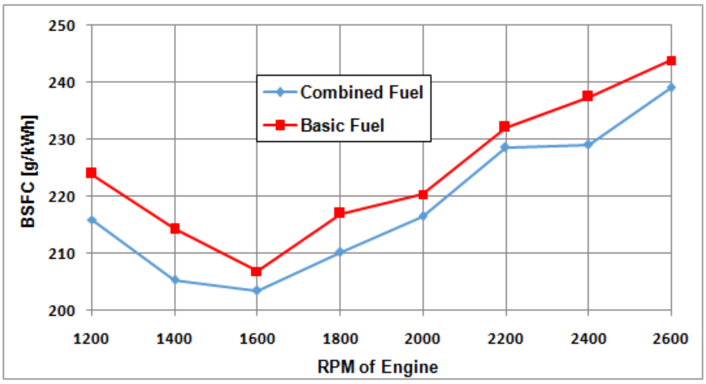
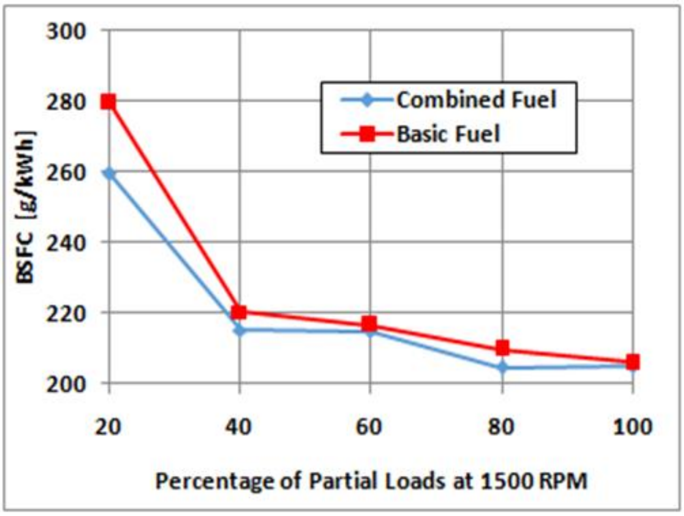


Figure 5. Brake specific fuel consumption vs. engine speed for the basic and combined fuels

4.2 The Brake Specific Fuel Consumption at Different Partial Loads

The BSFC for the base and combined fuels at constant 1500, 1800, and 2600 RPMs for various partial loads has been examined. As depicted in Figure 6, by increasing the percentage of loads, the BSFC decreases. The BSFC differences among the base and combined fuels are maximum at partial loads of 20%. However, by increasing the partial loads, the diagrams converge.



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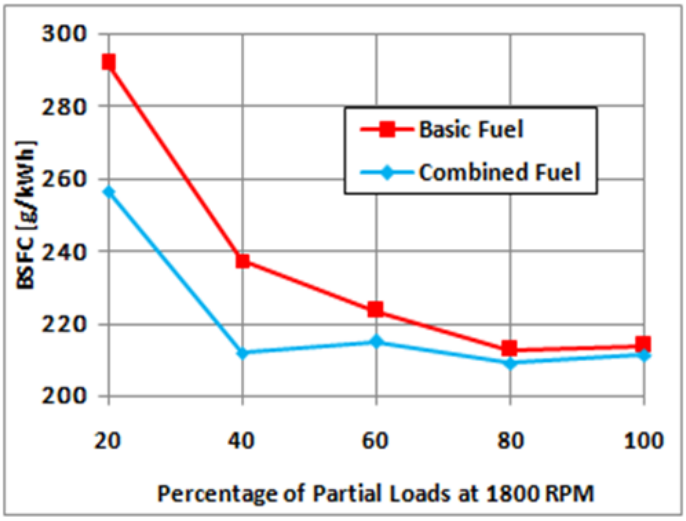

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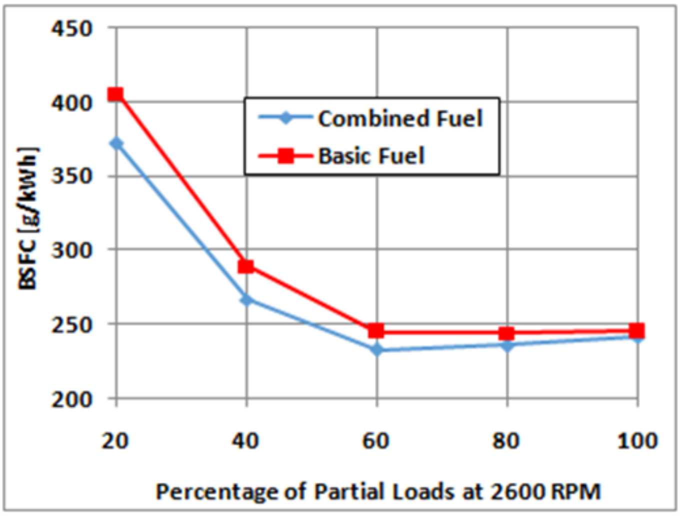

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Figure 6. The BSFC at constant: (a) 1500; (b) 1800; and (c) 2600 RPMs for different partial loads

4.3 Thermal Efficiency

The engine thermal efficiency, described in Eq. (4), is inversely proportional to BSFC tendency and the heating value of the tested fuel.

$$\mu_{th} = {}^{\mathrm{P}}\!/_{\mathring{m_f} \times Q_f} = {}^{3600}\!/_{BSFC \times Q_f} \tag{4}$$

where, Q_f[MJ/Kg] is heating value.

As shown in Figure 7, the thermal efficiency of the combined-fueled engine is higher in the whole range of engine speed since, according to Figure 5, the BSFC of combined fuel is lower than the base one. Moreover, the heating value of combined fuel is 1.07 times less than gasoline.

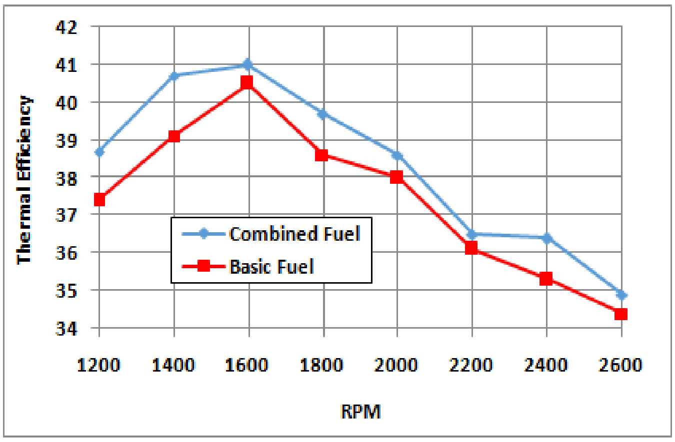


Figure 7. Thermal efficiency vs. engine speed for the basic and combined fuels

4.4 Engine Performance Characteristic

4.4.1 The interaction of fuel mixture and speed on engine power

Nanoparticles in combined fuels have a significant impact on fuel properties and combustion improvement, which leads to increases in engine power. Furthermore, the engine power is concerned with the engine's torque and speed. The power variation versus engine speeds for gasoline and compound fuel is depicted in Figure 8. Engine power rises with rising engine speed due to the increment in fuel consumption. At low RPMs, the conditions are almost the same for both fuels. However, at high RPMs, a boundary difference is observed.

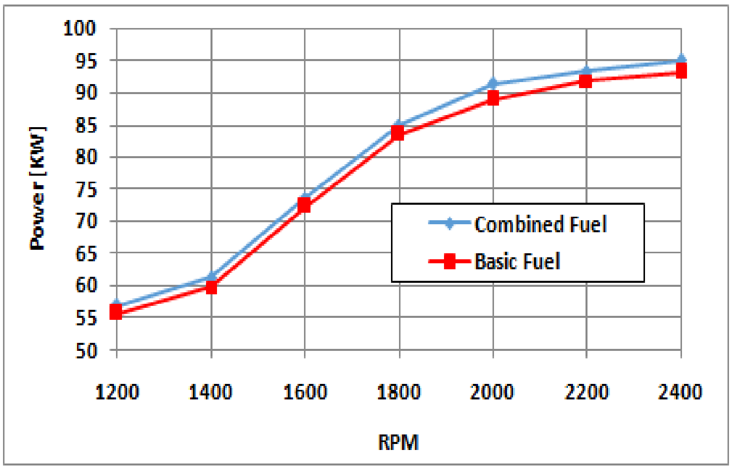
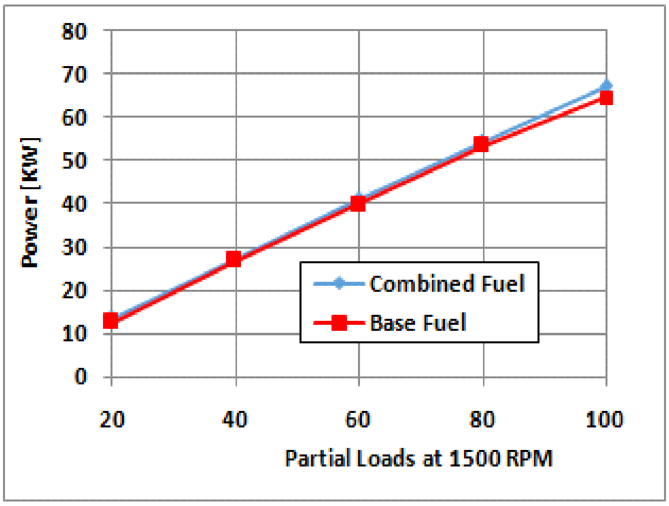


Figure 8. Engine power vs. engine speed for the basic and combined fuels

4.4.2 Interaction of fuel mixture and partial loads on engine power

Power variations of the studied engine versus different partial loads at constant RPMs of 1500, 1800, and 2600 are bestowed in Figure 9. Raising the partial loads at constant RPMs leads to the engine power increases. The positive impact of nanoparticles on increasing engine power has been observed at higher partial loads due to the nanoparticle activation energy.



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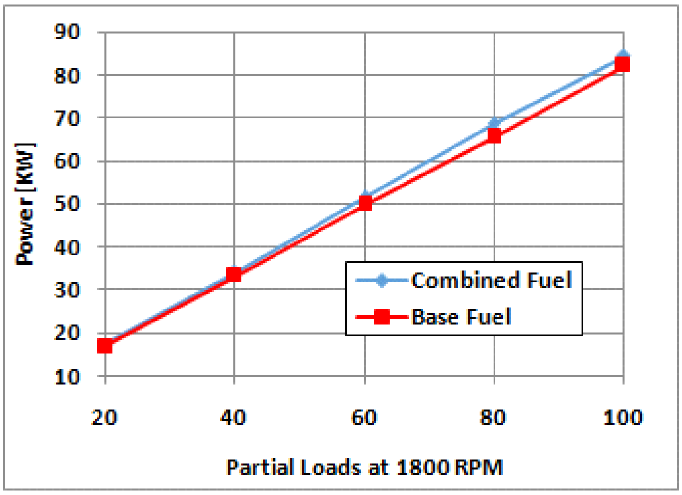

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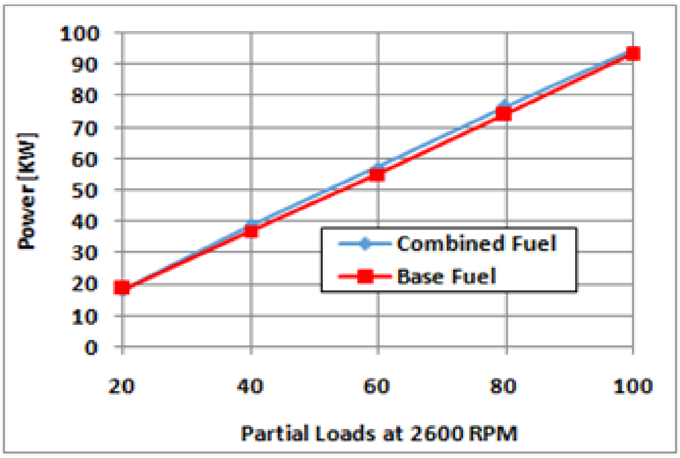

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Figure 9. Engine power at constant (a) 1500; (b) 1800; and (c) 2600 RPMs for different partial loads

4.4.3 The reciprocal effect of fuel mixture and speed on engine torque

The value of achievable torque from the engine drastically affects the specific fuel consumption. Engine torques for various engine speeds are presented in Figure 10. As the revolutions per minute increase from 1400 to 1800 RPM, the higher amount of fuel is consumed since the torque friction is significantly higher than the torque received from the dynamometer. When the torque received through the dynamometer overtake the torque friction, the cylinder can move more often and improve the torque.

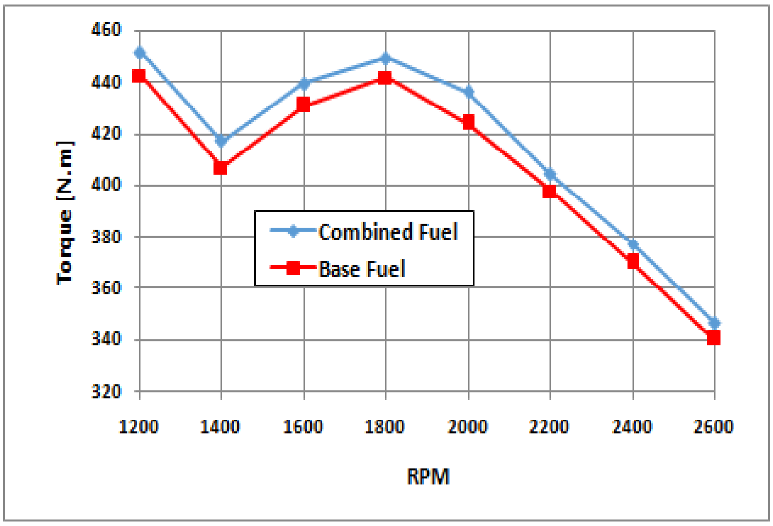


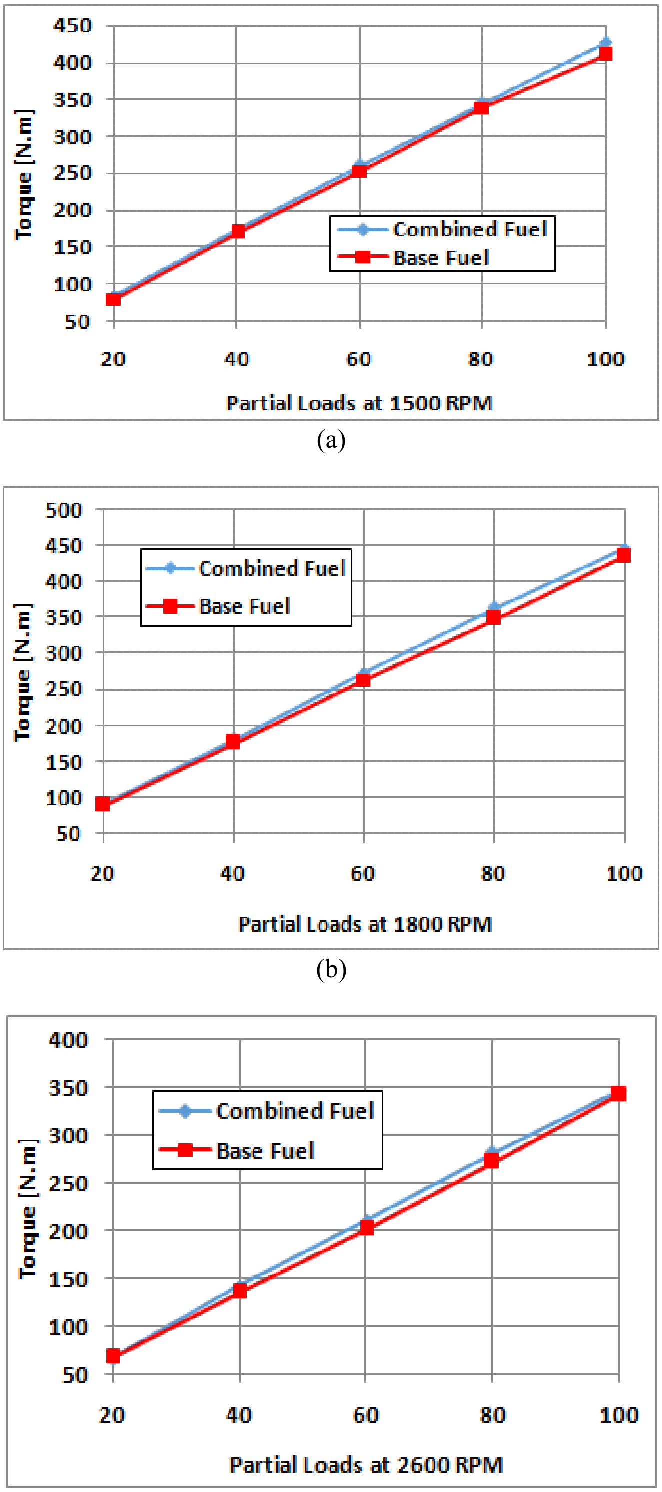
Figure 10. Torque vs. engine speed for the basic and combined fuels

4.4.4 Interaction effect of fuel mixture and partial loads on engine torque

Figure 11 represents the torque changes at different partial loads of constant 1500, 1800, and 2600 RPMs. According to Figure 11, increasing the partial loads at constant RPMs results in the improvement of engine torque. The impact of nanoparticles on increasing engine torque is achievable at higher partial loads due to the nanoparticle activation energy.

4.5 Engine Emission Characteristic

In this section, the effect of combined and base diesel fuel on engine emission characteristics is evaluated. Engine exhaust gas temperature and cylinder pressure in presence of mentioned fuels are crucial parameters in the engine emission discussion, which are presented in Figures 12 and 13. Addition of nanoparticles causes a decrease in the delay time, which results in lower exhaust gas temperatures compared to diesel fuel. In the 1600-2600 RPM range, exhaust gas temperature increases by accelerating RPM. Moreover, the average exhaust gas temperature raises roughly 20.2°C in the presence of TiO_2 nanoparticles in comparison to diesel fuel.



(a)

(b)

(c)

Figure 11. Engine Torque at constant: (a) 1500; (b) 1800; and (c) 2600 RPMs for different partial loads

On the other hand, the gain of the area/volume ratio by nanoparticle addition results in oxygen content advancement causing instantaneous combustion. For this reason, the maximum cylinder pressure raise. According to Figure 13, the average cylinder pressure increment with the exploitation of combined fuel at full loads is about 1.6 bar.

4.5.1 Interaction of fuel mixture and speed on engine pollution (soot)

The soot emissions reported in Figure 14 are considerably low for combined fuel at various RPMs. The addition of TiO_2 to gasoline improves the combustion process since the combustion temperature and in-cylinder pressure increase by utilizing combined fuel. Consequently, the soot emission reduces due to the catalytic effect of TiO_2. The engine smoke emission at 1500, 1800, and 2600 RPMs for combined fuel 21.21%, 38.46%, and 23.38% declines compared to base diesel, respectively.

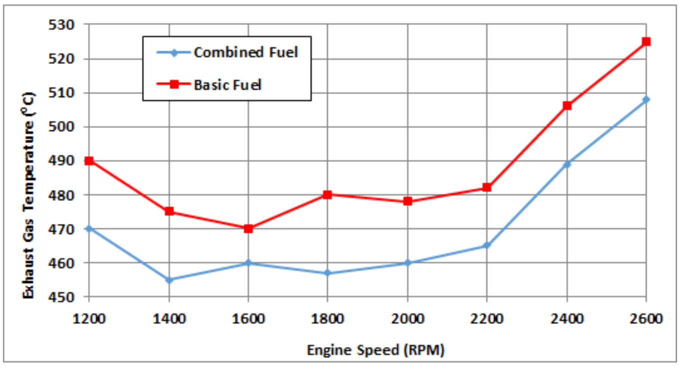


Figure 12. Exhaust gas temperature at various engine speeds and full load condition

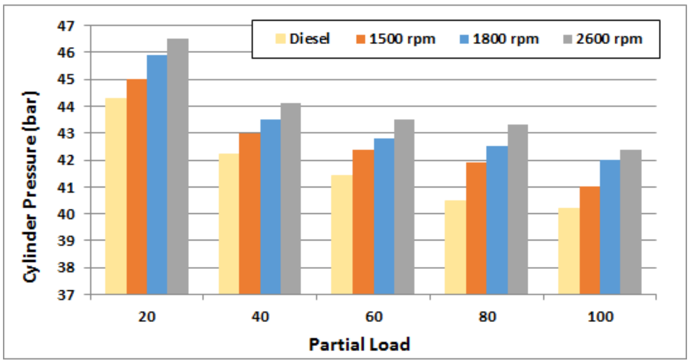


Figure 13. Cylinder pressure at various partial loads for 1500, 1800, and 2600 RPMs

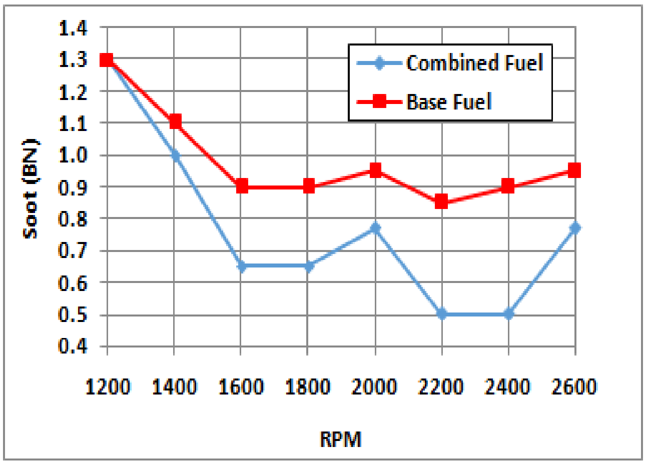


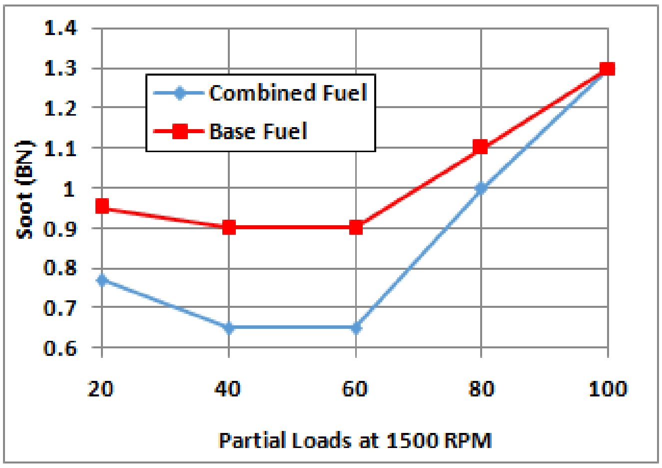
Figure 14. Soot vs. engine speed for the basic and combined fuels

4.5.2 Interaction of fuel mixture and partial loads on engine pollution (soot)

Figure 15 demonstrates the amount of soot emission versus various partial loads at constant 1500, 1800, and 2600 RPMs. It is clear that when partial loads increase, soot concentration for both fuels nearly increases. By comparing the two types of fuel, it is apparent that the soot emission in combined fuel is lower. However, at the partial load of 100 at 1500 RPM and 20 to 60 partial loads at 1800 RPM, the soot concentration of combined and base fuel is nearly the same.

4.5.3 Deviation in hydrocarbon and carbon monoxide

Complete fuel oxidation happens by the application of TiO_2 nanoparticles. Moreover, nanoparticles' activation energy prevents carbon sedimentation on the cylinder wall, resulting in hydrocarbon and carbon monoxide reduction, as depicted in Figure 16.



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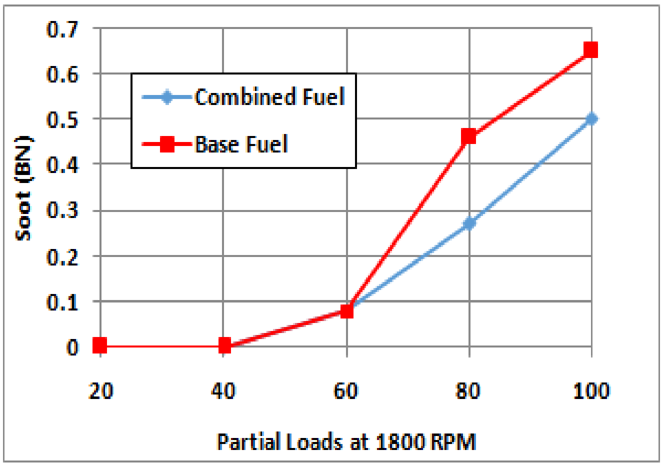

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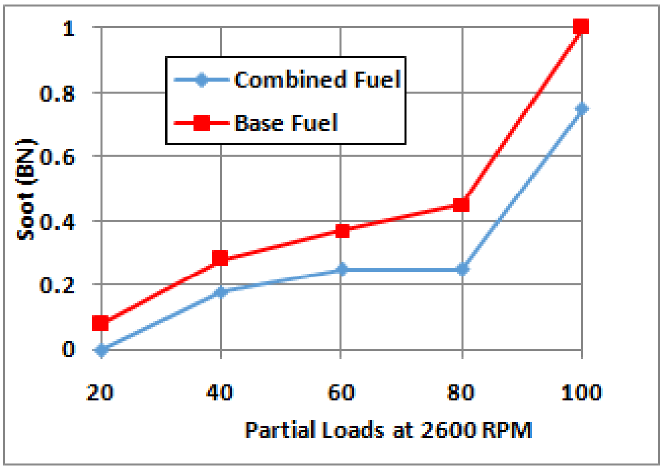

(c)

Figure 15. Engine soot at constant: (a) 1500; (b) 1800; and (c) 2600 RPMs for different partial loads

4.5.4 Deviation in NOx value

The most significant cause of NOx formation in compression combustion engines is the decomposition of gases at high temperatures. Calculations performed according to the Easy 6764 standard show that the amount of NOx in the combined fuel has increased compared to the base fuel because of the maximum temperature increment in the cycle.

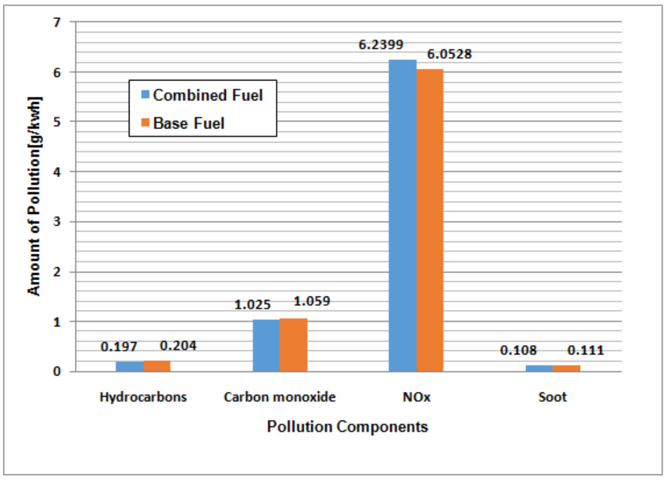

Figure 16. Emission indices comparisons for the basic and combined fuels in the 13 modes engine test

5. Conclusions

The primary objective of this study is to evaluate the performance and emission characteristics of the DI engine with the novel emulsion of 2.5 ppm TiO_2 nanoparticle additive for the first time on the performance and emission characteristics of the four-stroke combustion engine. These nanoparticles have been added to biodiesel or n-butanol blends in previous studies. For preventing environmental effect, 2.5 ppm of the TiO_2 nanoparticles are utilized. The results of this combined fuel have been compared with the base diesel fuel based on fuel properties, engine performance, and emission characteristics. The consequences of this study are as follows;

The addition of TiO_2 nanoparticles has increased the lighting point, viscosity, and density of the combined fuel compared to the base fuel up to 17.64%, 110.67%, and 9.63%, respectively.

Lower BSFC and higher engine power, torque, and thermal efficiency have been observed with the application of the proposed combined fuel at engine full load. Moreover, the positive impact of nanoparticles on increasing engine power and torque is obvious at higher partial loads due to nanoparticle activation energy.

The average exhaust gas temperature and cylinder pressure increment with the exploitation of combined fuel at full loads are approximately 20.2℃ and 1.6 bar.

The combined fuel has caused the 2.78%, 3.55%, and 3.32% reduction of soot, unburned hydrocarbons, and carbon monoxide, respectively, due to the improved combustion process and better atomization. However, the amount of NOx has increased up to 3.09% because of the high cycle temperature and short residual time in internal combustion. In the long run, the elimination of combustion chamber sediments by nanoparticles is expected to affect the combustion chamber to act as thermal insulation. In this way, the engine will run at lower temperature, and hence, NOx will decrease.

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Nomenclature

Greek symbols

μ_{th}	thermal efficiency, %

Subscripts

BSFC	brake specific fuel consumption, kg/kW h
TiO_2	titanium dioxide, ppm
CO	carbon monoxide, %
HC	hydrocarbon, ppm
NOx	nitrogen oxide, ppm
P	brake power, KW
W_R^+	total uncertainty
T	torque, N/m
Q_f	heating value, MJ/Kg
$\mathring{m}_f$	fuel consumption, $g/_h$