# Effects Of Fe2O3 and Al2O3 Nanoparticle-Diesel Fuel Blends on the Combustion, Performance and Emission Characteristics of a Diesel Engine

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# Effects of $Fe_2O_3$ and $Al_2O_3$ nanoparticle-diesel fuel blends on the combustion, performance and emission characteristics of a diesel engine

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**Abstract**

This research investigates the effects of the addition of $Fe_2O_3$ and $Al_2O_3$ nanoparticles (30, 60, and 90 ppm) and $Fe_2O_3$-$Al_2O_3$ hybrid nanoparticles to pure diesel fuel on the combustion, performance and emission characteristics of a diesel engine. The results indicated that fuel blends improved the combustion (in-cylinder pressure and heat release rate), performance (power, fuel consumption, and thermal and exergy efficiency), and emission characteristics of the engine. The results showed that the peak combustion pressure increased by 4% and the heat release rate was improved by 15% in comparison with pure diesel with the addition of the nanoparticles. Moreover, the rate of pressure rise increased by 18% compared to pure diesel with nanoparticle additives. Based on the results, the effects of $Fe_2O_3$ fuel blends on brake power, BTE, and CO emission were more than $Al_2O_3$ fuel blends, such that it increased power and thermal efficiency by 7.40 and 14%, respectively, and reduced CO emissions by 21.2%; moreover, the blends with $Al_2O_3$ nanoparticle additives in comparison with $Fe_2O_3$ nanoparticle blends showed a better performance in reducing BSFC (9%), $NO_x$ (23.9%), and $SO_2$ (23.4%) emissions. Overall, the $Fe_2O_3$-$Al_2O_3$ hybrid fuel blend is the best alternative if the performance and emission characteristics of the engine are both considered.

Keywords: Hybrid nanoparticle fuel blend, Diesel, Performance, Emission, Engine

**Abbreviations**

| | | | |
|---|---|---|---|
| D+Al30 | Diesel+ 30 ppm $Al_2O_3$ nanoparticles | D | Diesel |
| D+Al60 | Diesel+ 60 ppm $Al_2O_3$ nanoparticles | CO | Carbon monoxide |
| D+Al90 | Diesel+ 90 ppm $Al_2O_3$ nanoparticles | NOx | Nitrogen oxides |
| D+Fe30 | Diesel+30 ppm $Fe_2O_3$ nanoparticles | $SO_2$ | Sulfur dioxides |
| D+Fe60 | Diesel+60 ppm $Fe_2O_3$ nanoparticles | BTE | Brake thermal efficiency |
| D+Fe90 | Diesel+90 ppm $Fe_2O_3$ nanoparticles | BSFC | Brake specific fuel consumption |
| D+Fe30+Al30 | Diesel+30ppm $Fe_2O_3$ and 30 ppm $Al_2O_3$ nanoparticles | HRR | heat release rate |

## 1. Introduction

The high demands for fossil fuels, environmental problems, and global warming have necessitated the use of alternative and renewable fuels (Amiri and Shirneshan 2020). Today, using nanoparticle such as NO (Srinidhi 2017), $ZrO_2$ (Venu and Madhavan 2016b) and $TiO_2$ (Venu et al. 2019) additives in diesel engine fuels is proposed for improving performance, combustion, and emission properties of the diesel engines.

Heterogeneous combustion kinetics and ignition acceleration reaction, which result in high energy density, are some of the results of using fuel blends in diesel engines (Chen et al. 2018). Heterogeneous combustion occurs to complete forming the final products by the heat and is convectively transferred to the unburnt reactants. Moreover, the higher ratio of surface to volume helps to more rapid the oxidation during combustion and the higher the combustion enthalpy (Sivakumar et al. 2018). Other advantages of nanoparticles are high evaporation rate, good atomization, acceptable flame sustainability, and appropriate air-fuel mixing, all of which significantly reduce ID (Sivakumar et al. 2018). The good atomization of the fuel leads to an earlier start of the combustion process. Metal nanoparticle additives improve the combustion and performance efficiency of the conventional fuel; however, these additives have some downsides, the most important of which is that the exhaust gas of the engine fuelled with metal nanoparticles may contain solid metal oxides as the residual particulate matter which imposes a significant health risk, hence the necessity of incorporating a particulate filter on the engine using nanoparticle additives. Among other drawbacks, mention can be made of the risk of agglomeration, costly supply, and difficulty related to uniform dispersion (Basu and Miglani 2016). So it is needed to incorporate a particulate filter on the engine using nanoparticle additives. Chance of agglomeration, costly supply, and difficulty in uniform dispersion are other disadvantages. Because nanoparticle additives should lead to optimal emission and performance parameters of the engines, the extra costs pertaining to nanoparticle supply, mixture stability and dispersion process should be kept at a minimum. There are specific approaches to preventing nanoparticles from coagulating or settling down. The fundamental mechanism that prevents nanoparticle agglomeration and affects their stability is using surfactants, surface modification, steric repulsion, and electrostatic repulsion(Yu and Xie 2012).

There is some research on the impact of fuel blends on the performance, emission, and combustion properties of diesel engines. For instance, there have been reports regarding the effects of $TiO_2$ fuel blends on improving BTE and decreasing brake specific fuel consumption, HC and CO emissions (D'Silva et al. 2015); the effect of $TiO_2$ nano additives and exhaust gas recovery on increasing the performance and minimizing the exhaust emissions of biodiesel fuels (Venu et al. 2019); the impact of MgO and $SiO_2$ nano additives on reducing NOx and CO emissions and improving engine performance (Ozgur et al. 2015); the effect of $CeO_2$ nanoparticles in Lemongrass oil emulsion fuel on enhancing the engine performance and improving HC and CO emissions (Annamalai et al. 2016), and the influence of cerium oxide-calophyllum biodiesel in the engine with five-hole nozzle (NH5) injectors on decreasing HC and NOx emission and improving BSFC.

In an experimental research, Soukht Saraee et al. (2017) observed that NOx and HC were reduced with using $CeO_2$ nanoparticles-diesel fuel blends, while carbon monoxide emissions were slightly increased. Besides, there was a reduction in BSFC, and no significant changes were reported in terms of brake power compared to pure diesel fuel.

In another experimental study (Örs et al. 2018), the influence of a mixture of biodiesel, titanium dioxide, n-butanol, and diesel was investigated on the emission and performance parameters of a CI engine. An increase was observed in the combustion pressure and HRR using $TiO_2$, improving brake torque and power by up to 10%. Moreover, BSFC was reduced by around 30% following the addition of $TiO_2$ nanoparticles. HC, and CO emissions were reduced while NO and $CO_2$ emissions increased. The authors further reported that waste frying oil biodiesel, $TiO_2$, and normal butanol additive were capable of enhancing the combustion, emission, and performance characteristics.

Also, Najafi (2018) investigated that adding carbon nanotubes and Ag nanoparticle blend to biodiesel and diesel increased the peak of combustion pressure and the peak of PRR in comparison with pure diesel fuel. Also, the HRR of the diffusion combustion phase was higher due to the higher oxygen content of the blended fuels that have improved the diffusion combustion phase and decreased the combustion duration. Moreover, ID was reduced by around 9% utilizing biodiesel+120 ppm carbon nanotubes additive compared to conventional fuel.

Among the nano additives, $Al_2O_3$ and $Fe_2O_3$ nanoparticles have attracted scientific attention. Iron nanoparticles (ferrocene) have been dissolved in the fuel as a combustion catalyst in previous studies (Braun et al. 2006).

In another work, Ozgur et al. (2015) showed that blending nanoparticle additives such as $Al_2O_3$, MgO, $TiO_2$, ZnO, $SiO_2$, and $Fe_2O_3$ with conventional diesel fuel reduced NOx emissions.

Ooi et al. (2016) used graphite oxide, aluminium oxide, and cerium oxide nanoparticles to investigate the combustion parameters of a CI engine. A notable improvement in combustion efficiency and reducing the harmful emissions were further observed using nanoparticles in the diesel engine.

Chen et al. (2018) conducted the some experimental tests on a diesel engine to investigate the effect of nanoparticles (alumina, carbon nanotubes, $SiO_2$) blended with diesel fuel. According to the results, the brake specific fuel consumption was dropped by up to 20% and BTE was increased by 19%. Moreover, $SiO_2$ blends were more effective than alumina blends due to improving combustion pressure, BSFC, BTE, and CO emissions. However, carbon nanotube blended with diesel enhanced NOx emissions.

The effect of $Al_2O_3$ nanoparticle addition to the blend of biodiesel, diesel, and ethanol on various injection strategies was studied by Venu and Madhavan (2016a) who showed that $Al_2O_3$ addition at advanced timing augmented the peak pressure, HC, CO, and NOx and reduced $CO_2$ and the ignition delay ID. However, $Al_2O_3$ addition with retarded timing resulted in lower cylinder pressure and reduced HC, CO, NOx, and smoke opacity. The brake specific fuel consumption and combustion duration were further observed to be reduced during retarded timing by use of $Al_2O_3$. Finally, the results of this research revealed that alumina ameliorated the combustion, performance, and emission parameters of the engine.

Mandilas et al. (2016) evaluated the combustion of 25-85 nm iron nanoparticles as a replacement fuel for internal engines under idealized conditions (combustion in customized shock tube), engine-like conditions (combustion in a constant-volume vessel) and real engine conditions. They reported that the combustion of Fe nanoparticles could be done in CI engine with a slight modification; however, there exist certain technological challenges associated with ignition and scavenging that reduce the chances of good combustion.

In another experimental study (Sadhik Basha and Anand 2012) the performance and emission of a CI engine fuelled with water-alumina-diesel emulsion were studied. Based on the results, alumina fuel blends significantly ameliorated the engine performance and reduced the emission of pollutants.

Gumus et al. (2016) showed that adding 50 ppm $Al_2O_3$ or CuO nanoparticles to neat diesel caused an increase in the brake power and torque and a reduction in HC, CO, $NO_x$ emissions. The nanoparticles concentration was assumed constant (50 ppm) and the hybridization effect was not presented.

Elahi M.Soudagar et al. (Soudagar et al. 2018) in a review paper reported that there is further scope for enhancement in fuel properties and to overcome the drawbacks by the addition of nanoparticles to bio fuels. The results demonstrated an improvement in the thermo-physical properties, enhancement in the heat transfer rate, and stabilization of the fuel mixtures. Also, there was an increase in the engine performance parameters and a reduction in exhaust emissions depending on the dosage of nanoparticle additives.

In the El-Seesy et al. (2018) work, the effect of alumina nanoparticles ($Al_2O_3$) into Jojoba biodiesel-diesel blend on the performance and exhaust emissions of a diesel engine was investigated. The results revealed that using of $Al_2O_3$ additives can improve all engine performance characteristics; and the best emission characteristics were obtained at the dose level of 20 mg/l, where NOx, CO, HC, and smoke opacity were significantly reduced. According to the comparisons of engine performance and emissions, the recommended concentration of $Al_2O_3$ in Jojoba biodiesel-diesel blend was concluded to be 30 mg/l, which gave remarkable enhancement in all engine parameters.

The engine performances and exhaust emissions of aluminium oxide ($Al_2O_3$) and silicon dioxide ($SiO_2$) nanoparticles blended in palm oil methyl ester were evaluated in Adzmi et al. (2019). Various engine loads at a constant engine speed of 1800 rpm were applied during engine tests. The results showed that the highest maximum pressure of nanoparticle fuel increases by 16.3% compared to POME test fuel. Besides, the engine peak torque and engine power showed a significant increase of 43% and 44%, respectively. Moreover, the emissions of nanoparticles fuel indicated a large decrease in NOx and $CO_2$, and a slight decrease in CO emission.

Based on the literature review, the utilizing of nanoparticle additives was found to improve engine power, torque and combustion parameters and reduce BSFC. Moreover, nanoparticle additives cause a reduction in hydrocarbon, carbon monoxide, and smoke emissions. However, there are negative effects for using oxygenated nanoparticle additives in increasing the NOx emission because of providing oxygen molecules in a chain reaction. Literature reviews also showed that there are so far no research focused on the using mixture of $Fe_2O_3$ and $Al_2O_3$ nanoparticles (Hybrid fuel blend) in diesel engine; therefore, the objective of this study is to present a comprehensive study which investigates and compares the effects of different concentrations of $Fe_2O_3$ and $Al_2O_3$ nanoparticles and their mixture ($Fe_2O_3$-$Al_2O_3$ Hybrid fuel blend) in a diesel engine. To this end, $Al_2O_3$ and $Fe_2O_3$ and $Fe_2O_3$-$Al_2O_3$ Hybrid nano particles with 30, 60 and 90 ppm concentrations was blended in diesel fuel and their effect on the combustion (in-cylinder pressure and heat released rate), performance (torque, brake power, BSFC, BTE, and exergy) and emission (CO, NOx, and $SO_2$) parameters of a CI (diesel) engine under various rpms and loads is presented.

## 2. Materials and Methods

In this study, aluminum oxide ($Al_2O_3$) and iron (III) oxide ($Fe_2O_3$) nanoparticles were supplied from Tamadkala Shop. Three concentrations of 30, 60, and 90 ppm of each nanoparticle were used to evaluate the impact of nanoparticles on the performance and gaseous emissions of a CI engine.

### *2.1 Preparation of different fuel blends*

The most common method for stabilizing nanoparticle additives in fuels is the use of surfactants (Chen et al. 2018), which results in the proper distribution of nanoparticles in the fuel, hence better stability(Ghadimi et al. 2011; Yu and Xie 2012). In the current study, SPAN 80 surfactant was used to create the relative stability of the fuel (0.045mgr SPAN80 for 30ppm nanoparticles). In order to mix nanoparticles with the fuel, an ultrasound bath with a frequency of 40 kHz, a power of 240W, and a temperature of 50℃ was used for 40 minutes. A slight amount of nanoparticle agglomeration was observed after 2 days. For rehomogenizing, the fuel blend was positioned under ultrasonic waves prior to use in the engine. The engine was fuelled with different fuel blends during the tests: pure diesel, D+Fe30, D+Fe60, D+Fe90, D+ AL30, D+ AL 60, D+ AL 90 and D+Fe30+AL30. Properties of the fuel mixtures and the images of the prepared fuel blends were presented in Appendix 1. It is to be noted that the hybrid fuel blend is black because the colour of $Fe_2O_3$ nanoparticles is dominant.

### *2.2 Test set-up and instruments*

Figure 1 and Table 1 show the test set up and engine specifications, respectively.

Figure 1: The engine test set-up

Table 1: Diesel engine specifications

| | |
|---|---|
| Engine Model | 186F |
| Manufacturer | Zhejiang Wenxin Mechanical & Electrical Co. Ltd, China |
| Type | Air-cooled, Single-cylinder, Four-stroke |
| Bore | 86 mm |
| Stroke | 70 mm |
| Rated power | 5.7 kW at 3000 rpm |
| Compression ratio | 19 |
| Maximum torque speed | 1800 rpm |

So as to measure the pollutant emissions of the engine, including carbon monoxide (CO), nitrous oxides ($NO_x$), and sulfur dioxides ($SO_2$), Testo350 gas analyzer was used. The accuracy of the measured parameters is shown in Table 2. Engine tests were performed at various rpms and full engine load to determine brake power, torque, and BSFC; the tests were further carried out at 25, 50, 75, and 100% engine loads (and rated speeds of the engine to measure pollutant emissions. The 3-time repetition was applied for the experiments of each fuel blend and the average of measurements was also reported. The pressure sensor (Kistler) was utilized to measure the combustion pressure (Table 3). A crankshaft angle sensor was further employed to measure the crankshaft position and determine the in-cylinder pressure against the crank angle. Moreover, the net HRR (heat release rate) was determined by Eq. (1) based on the first law of thermodynamics (Li et al. 2015; Rakopoulos et al. 2010):

$$\frac{dQ}{d\theta} = \frac{1}{\gamma - 1}\left[\gamma P \frac{dV}{d\theta} + V \frac{dP}{d\theta}\right] \tag{1}$$

The uncertainties of the experimental parameters are affected by different error sources, namely, the random fluctuation of employed instruments, the calibration of the test bed, the observation accuracy, and the methodology of the experiments (Singh and Verma 2019). For directly measured parameters, the measurement uncertainties are defined by the accuracies of the experimental instruments. For computed parameters, the measurement uncertainties are determined based on the principle of the root-mean-square method and the measurement accuracies of the measured parameters (Li et al. 2015; Rahman et al. 2013):

$$e_R = [\left(\frac{\partial f}{\partial X_1} e_1\right)^2 + \left(\frac{\partial f}{\partial X_2} e_2\right)^2 + \cdots + \left(\frac{\partial f}{\partial X_n} e_n\right)^2]^{\frac{1}{2}} \tag{2}$$

Where $e_R$ is the measurement uncertainty of the computed parameter, f is the given function of the computed parameter, $e_1$, $e_2$, and … are the measurement uncertainties of the related measured parameters. The uncertainties of the measured and computed parameters presented in Table 2.

Table 2: The accuracies and uncertainties of the measurements and calculated parameters

| Measured or calculated parameter | Measurement range | Accuracy of measurement/ overall uncertainty in computation |
|---|---|---|
| Speed | 0–2500 rpm | ±1 rpm |
| CO | 0-10% | ± 0.01 vol.% |
| $NO_X$ | 0-5000PPM | ±1 ppm |
| $SO_2$ | 0-2000PPM | ±1 ppm |
| Torque | 0–40Nm | ±0.1 Nm |
| Brake power | - | ±0.014 kW |
| BSFC | - | ±3 gr/kWh |
| BTE | - | ±0.1% |

Table 3: Technical specifications of the in-cylinder pressure sensor

| | |
|---|---|
| Model | 6613CA |
| Measurement range | 0-250 bar |
| Sensitivity | 10 mV/bar |
| Sensitivity to acceleration | 0.001 bar/g |
| Frequency range (-3 dB) | 0.032- 20 000 Hz |

*2.3 Exergy efficiency*

Availability or maximum reversible work is the ultimate potential of a system for work production. For actual states, the output work done by the system is lower than maximum reversible work due to the irreversibility of the system. Therefore, the exergy efficiency can be defined as follows(Şanli and Uludamar 2019):

$$\varepsilon = \frac{\dot{W}_b}{\dot{X}_{Fuel}} \tag{3}$$

Where $\dot{W}_b$ is the engine brake power and $\dot{X}_{Fuel}$ is the fuel exergy input rate calculated by:

$$\dot{X}_{Fuel} = \dot{m}_{Fuel} e_{Fuel} \tag{4}$$

Where $\dot{m}_{Fuel}$ is the mass flow rate of the fuel and $e_{Fuel}$ is the chemical exergy of the fuel calculated by:

$$e_{Fuel} = [1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\frac{S}{C}\left(1.216901\frac{H}{C}\right) H_u] \tag{5}$$

$H_u$ is the LHV of the fuel and H/C=0.1488, O/C=0 and S/C=0.07467 are mass fractions of hydrogen, oxygen, and sulfur content to carbon content in the fuel, respectively.

## 3. Results and Discussions

The effect of using $Al_2O_3$ and $Fe_2O_3$ nano diesel fuels are presented in previous researches. However, the detailed studies on the optimization and comparison of these nano fuels are not presented so far. The present study, compares the effect of adding $Al_2O_3$ and $Fe_2O_3$ and their hybrids on performance and emissions of a diesel engine.

### *3.1 The properties of the nanoparticles*

The properties of the nanoparticles used in this study are also presented in Table 4. Moreover, Figures 2 and 3 show the TEM and SEM analysis of the nanoparticles, confirming the size of nanoparticles presented in Table 4. These figures further show the uniformity in size and shape of nanoparticles which is a desirable feature for nanoparticles.

Table 4: nanoparticles properties used in the current study

| Type | Size | Purity | SSA | Colour |
|---|---|---|---|---|
| Iron (III) oxide nanoparticle ($Fe_2O_3$, alpha) | 20-40 nm | +98% | 40-60m$^2$/g | Dark brown |
| Aluminium oxide nanoparticle ($Al_2O_3$, gamma) | 20 nm | +99% | >138m$^2$/g | white |

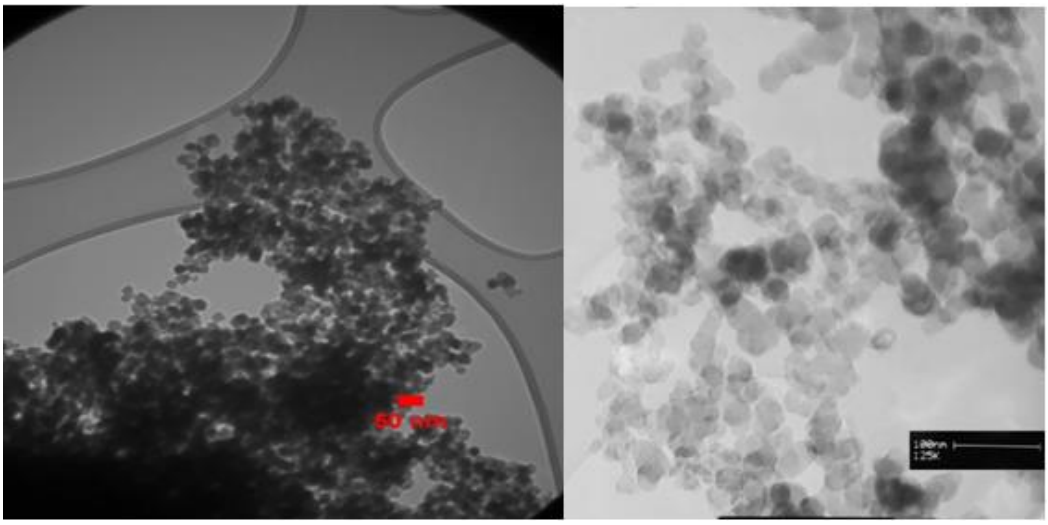


Figure 2: TEM and SEM analysis of $Al_2O_3$ nanoparticles

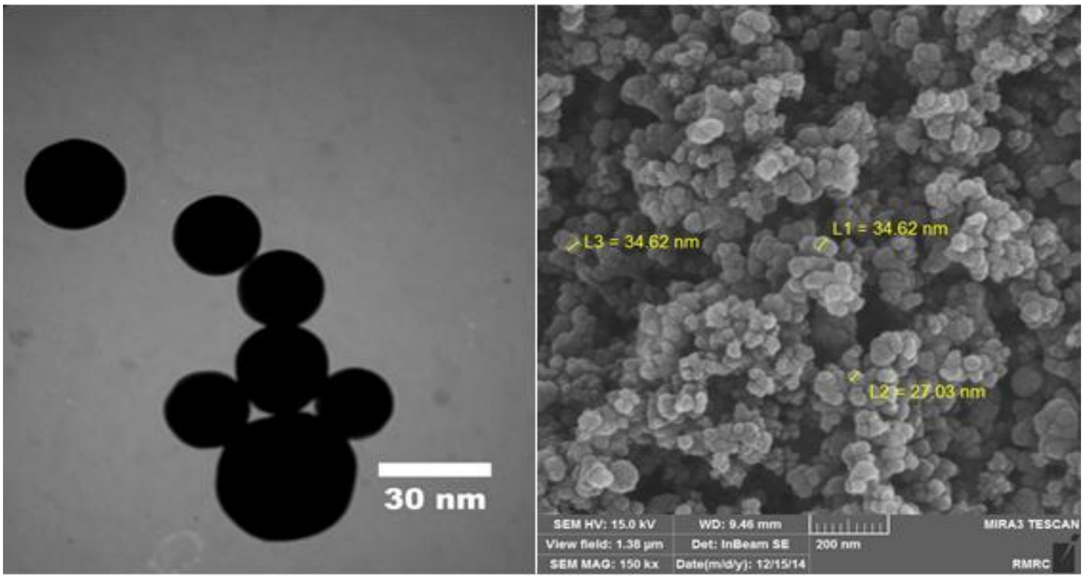


Figure 3: TEM and SEM analysis of $Fe_2O_3$ nanoparticles

*3.2 Effect of nanoparticle on the combustion parameters*

Figures 4 and 5 show the variation of in-cylinder (combustion) pressure versus crank angle for neat diesel and D+Fe90, D+Al90, D+Fe30+Al30 fuel blends at the speed of 1800 rpm and under 50% and full engine load, respectively. The rate of pressure rise at the speed of 1800 rpm under 50% and full engine load is further shown in Figures 6 and 7, respectively.

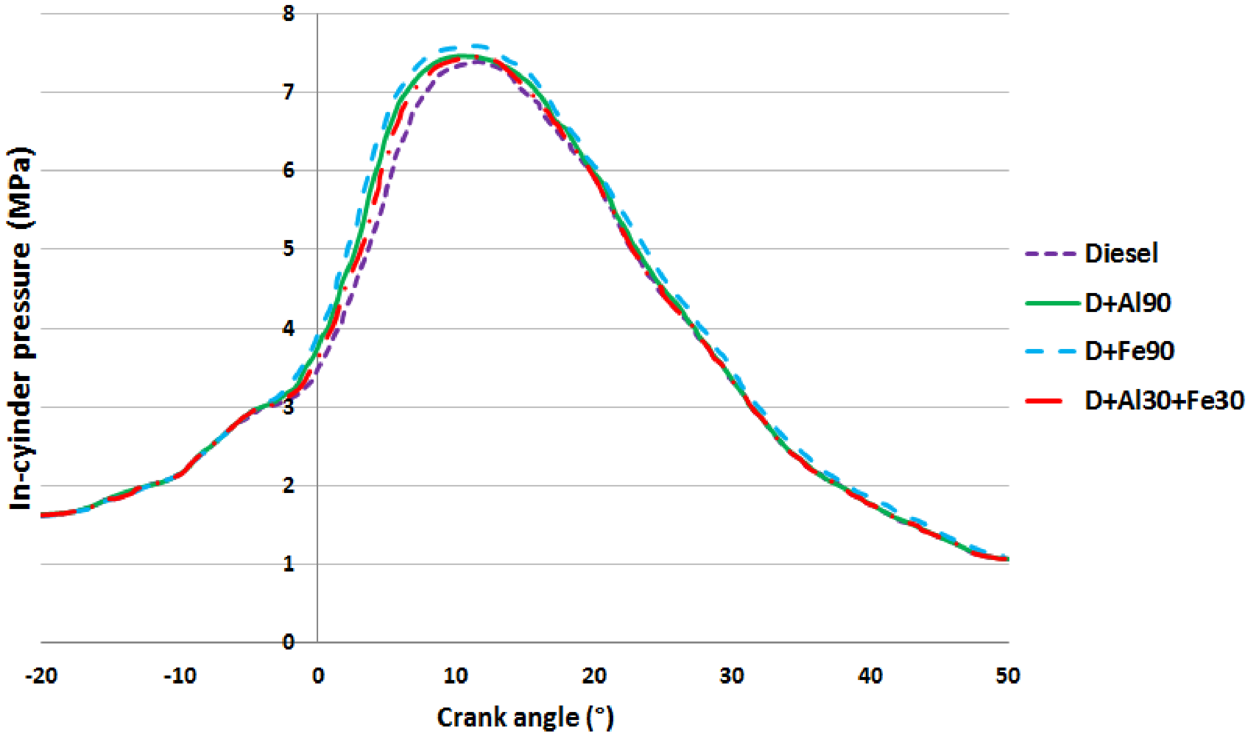


Figure 4: In-cylinder pressure variations versus crank angle at 50% engine load

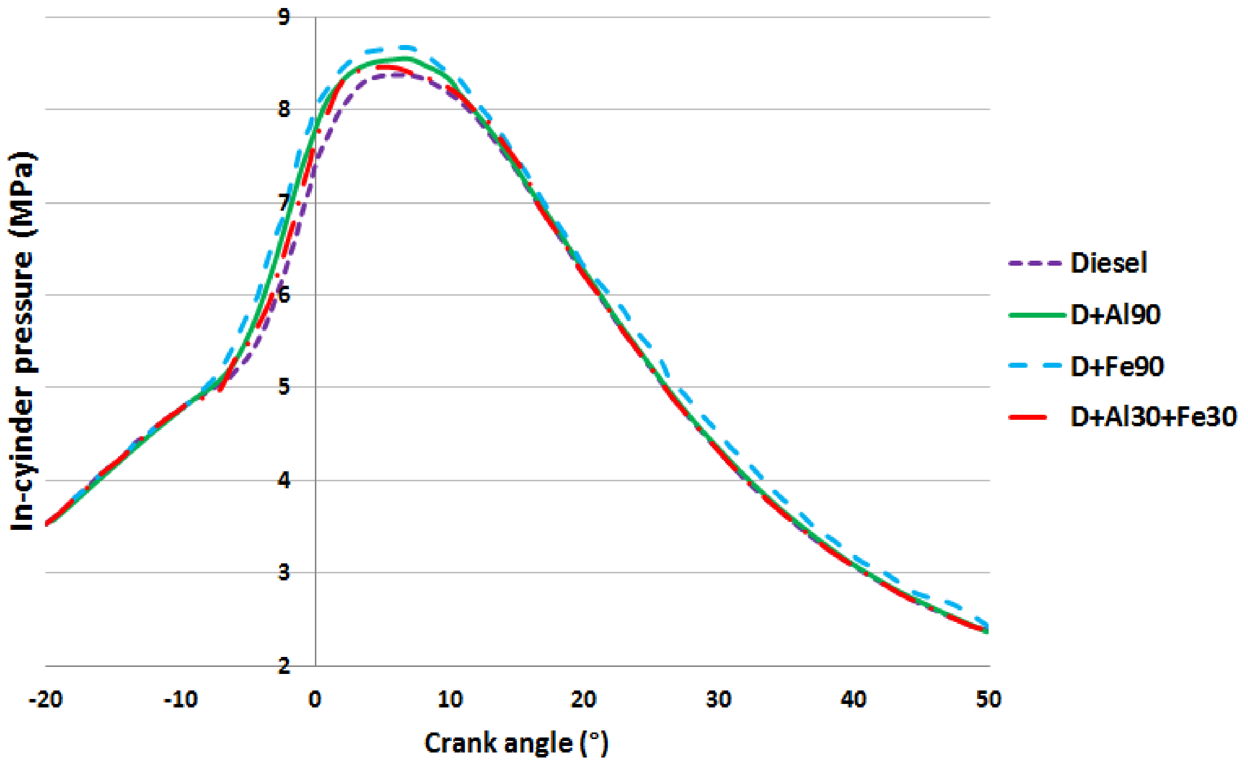


Figure 5: In-cylinder pressure variations versus crank angle at full engine load

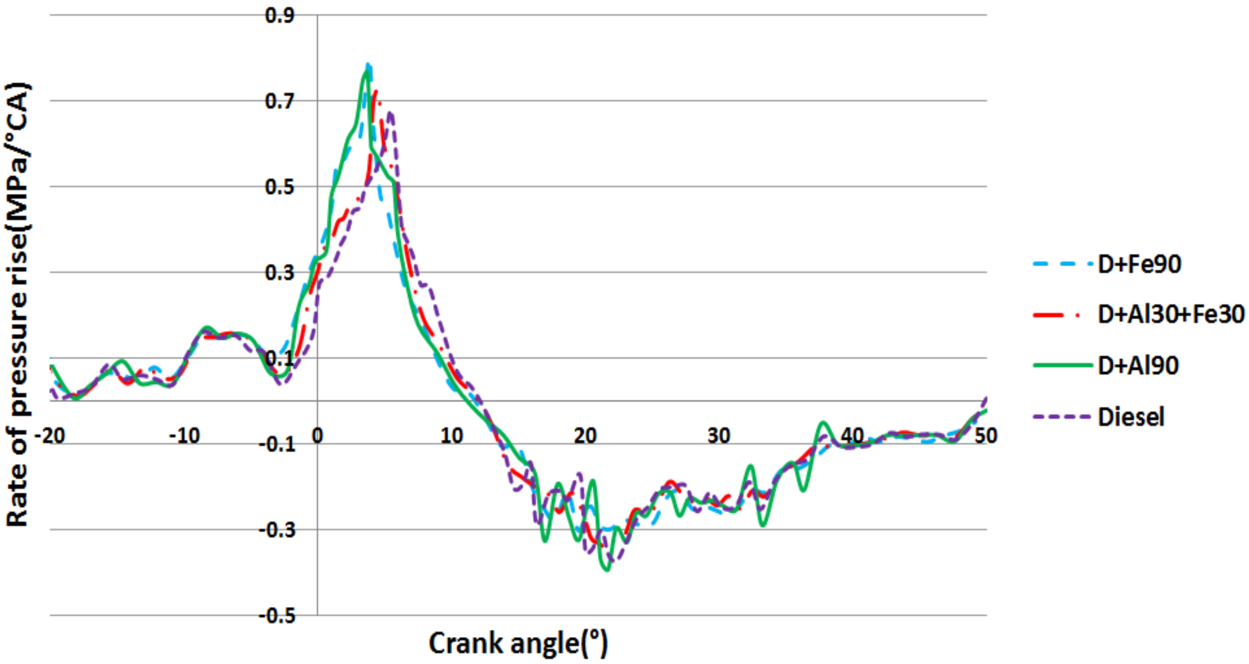


Figure 6: Variations of the rate of pressure rise against crank angle at 50% engine load

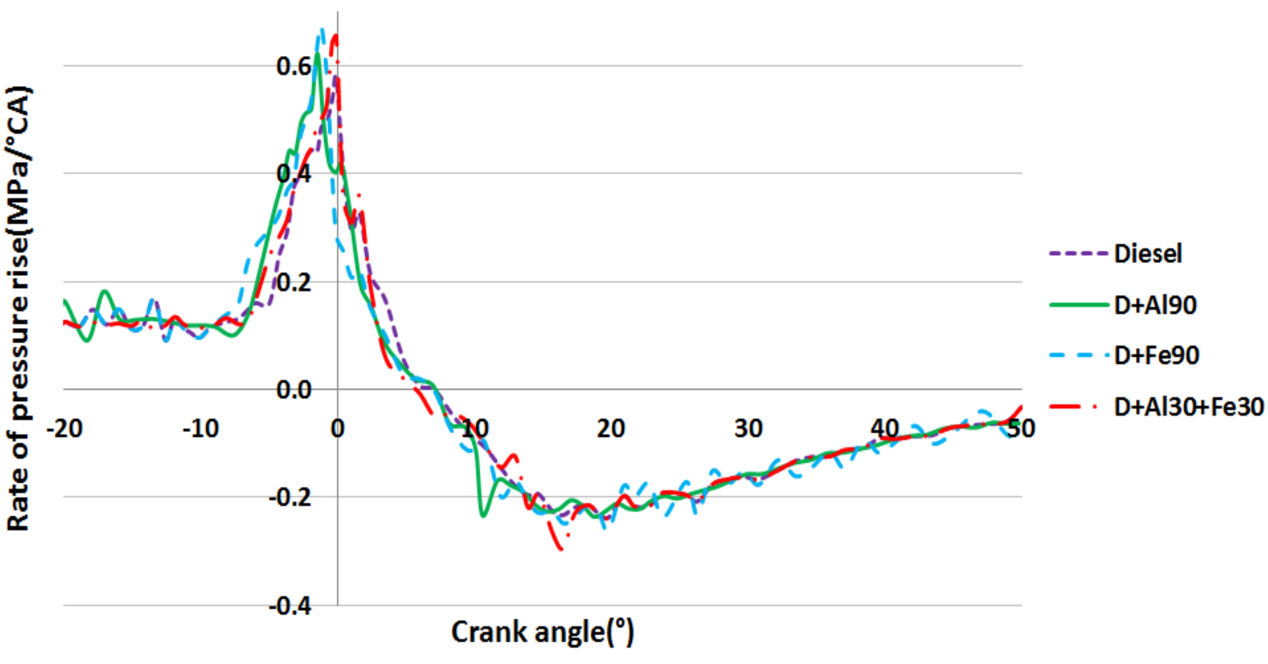


Figure 7: Variations of the rate of pressure rise against crank angle at full engine load

According to the results, the combustion conditions (especially ignition delay of diesel fuel) tend to be better with the addition of nanoparticles, and the in-cylinder pressure increased. This is due to the effect of metal oxide nanoparticles to reduce the time of fuel evaporation and increase the efficiency of the combustion (Rao and Srinivasa Rao 2015). Moreover, aluminum oxide and iron oxide nanoparticles have activity as an oxygen buffer that releases oxygen and promotes the complete combustion(El-Seesy et al. 2018). D+Fe90 blend was observed to have the highest in-cylinder pressure among other fuel blends owing to the higher LHV and lower ignition delay. The addition of nanoparticles further increased the maximum cylinder gas pressure. The combustion peak pressure developed with D+Fe30+Al30, D+Al90, and D+Fe90 blends was enhanced by 0.7%, 1.2% and, 3.1% respectively compared with neat diesel at 50% engine load. Also, the maximum cylinder gas pressure of the engine fuelled with D+Fe30+Al30, D+Al90, and D+Fe90 blends increased by 1.7%, 2.8% and, 3.6% respectively compared with neat diesel under full engine load. According to the results, the maximum rate of pressure rise belonged to the D+Fe90 blend occurring earlier for all blends under 100% load condition compared to 50% engine load owing to the higher combustion temperature condition which reduces the ignition delay of the fuel blends.

Figures 8 and 9 show the variation of HRR against the crank angle for neat diesel and D+Fe90, D+Al90, and D+Fe30+Al30 fuel blends at the speed of 1800 rpm under 50% and full engine load conditions, respectively.

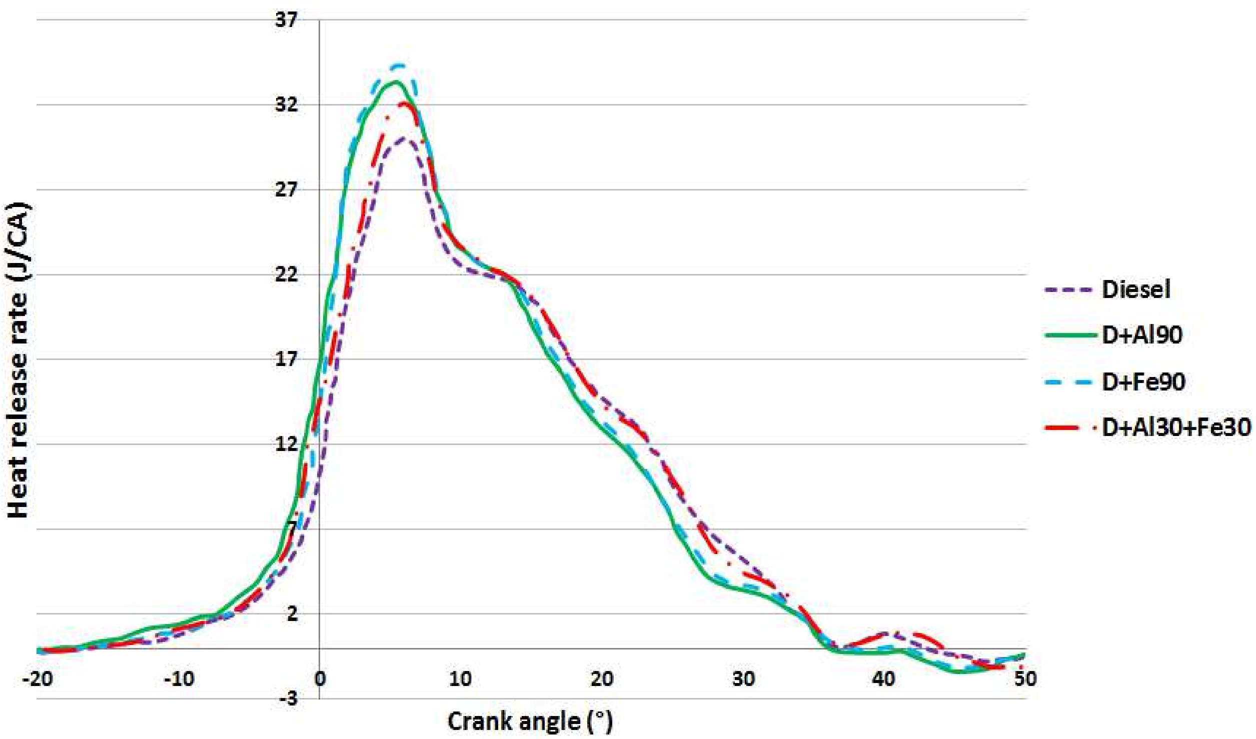


Figure 8: Variations of the HRR versus crank angle at 50% engine load

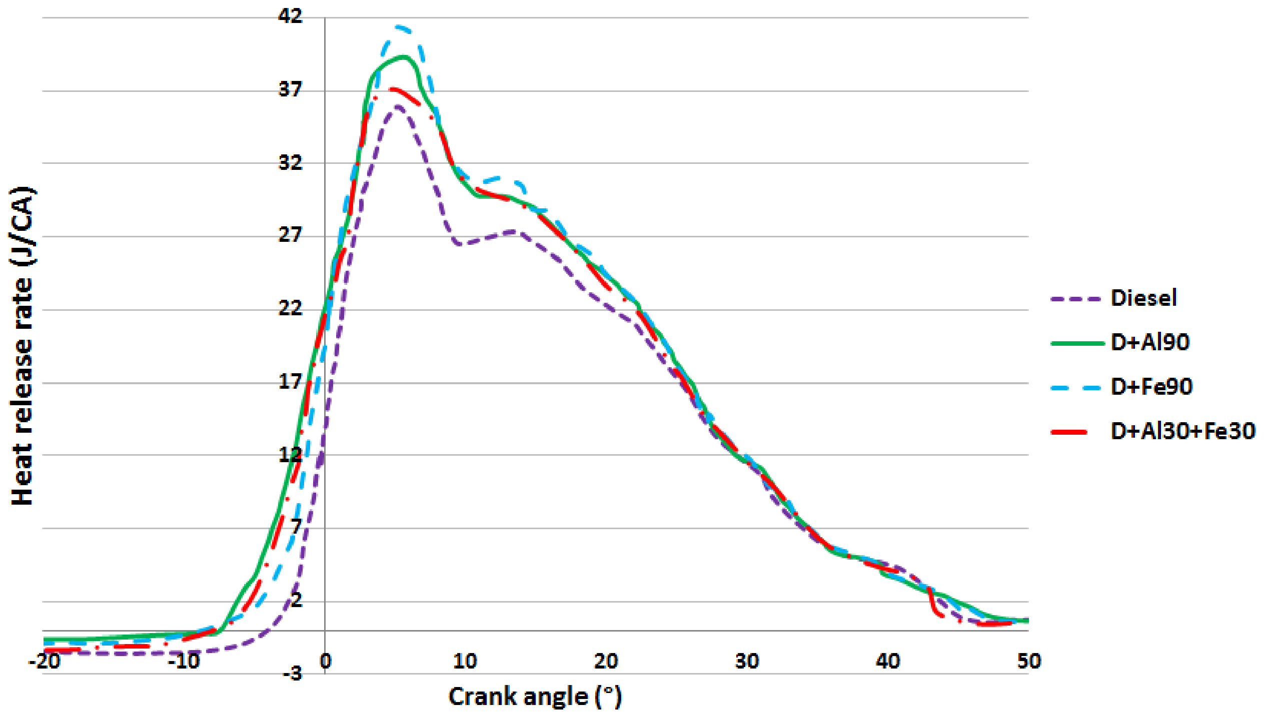


Figure 9: Variations of the HRR versus crank angle at full engine load

Based on the results, the rate of heat release was enhanced for all fuel blends compared to the diesel fuel without nanoparticle, which is in agreement with the results of Srinidhi et al. (Srinidhi et al. 2019) regarding nickel oxide nanoparticles. This is owing to the reduced ID and accelerated the process of the combustion as a result of nanoparticle addition which causes an improved combustion condition compared with neat diesel fuel (Aalam et al. 2015; Chen et al. 2018).
The maximum heat release rate of the engine was observed to increase by 3.4%, 9.4%, and 15.2% concerning fuel blends D+Fe30+Al30, D+Al90 and D+Fe90, respectively, compared to the neat diesel at 100% load. Furthermore, the maximum HRR increased by 6.8%, 11%, and 13.9% as regards the engine fuelled with D+Fe30+Al30, D+Al90, and D+Fe90 blends, respectively, compared to the neat diesel at 50% engine load.
Because the thermal conductivity of aluminum oxide nanoparticles (30 W/m.K) is higher than that of iron oxide nanoparticles (15 W/m. K), $Al_2O_3$ nanoparticle can distribute the heat in the compression cycle (Takeda et al. 2009). Therefore, the highest heat release rate in the compression process belonged to the D+AL90 blend. On the contrary, $Fe_2O_3$ nanoparticles with higher LHV and lower ignition delay achieved the highest rate of heat release, and the highest HRR enhanced for all blends at higher loads owing to the better combustion in this condition(Chen et al. 2018). Compared with other studies, Najafi (2018) reported an increase of 24% and 28% in peak pressure rise rate and heat release rate respectively with using nanoparticle additives in a diesel engine. In another paper (Shaafi and Velraj 2015), the maximum HRR and peak pressure enhanced around 4% and 16% for diesel engine fuelled with nanoparticle additives.

*3.3 Effect of nanoparticle on brake torque*

For any diesel engine, torque is a function of its volumetric efficiency. Since cylinder filling is incomplete, volumetric efficiency is reduced at higher speeds, resulting in reduced engine torque (Pulkrabek 1997). Moreover, the pressure produced through combustion depends on the LHV of the fuel. Figure 10 shows the engine torque values versus rotational speed in terms of deferent nanoparticle-diesel fuel blends at full load.

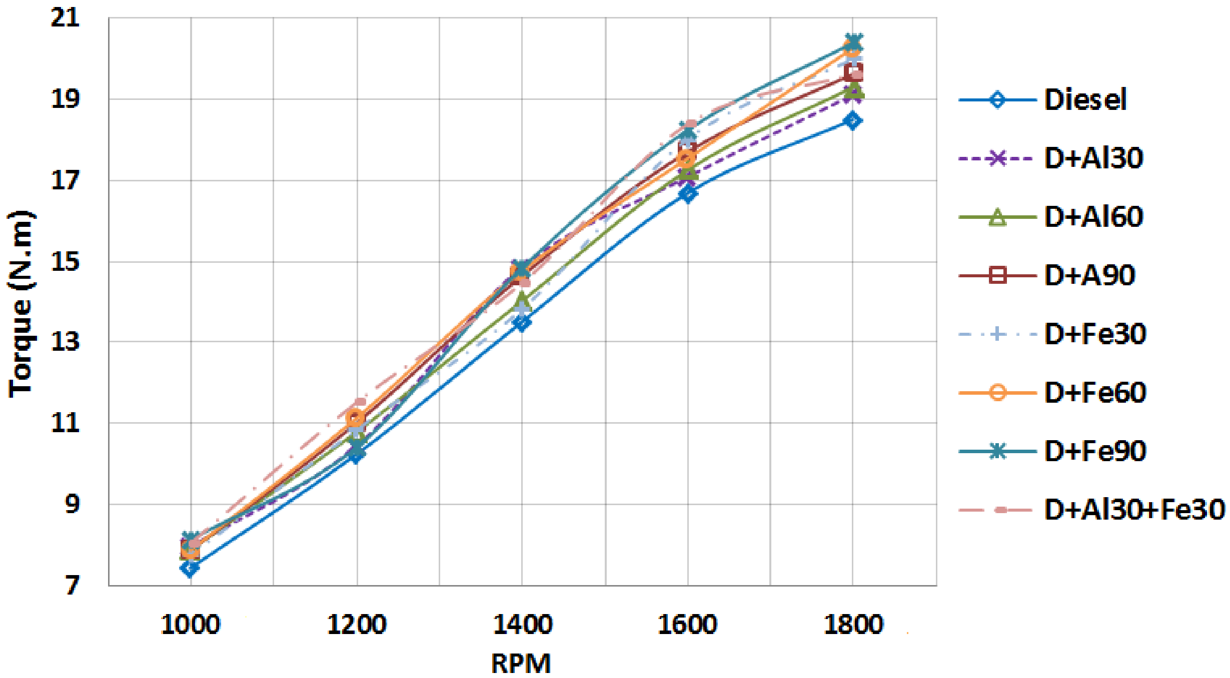


Figure 10: Brake torque values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

As observed, for all blends, with increasing the rotational speed, the brake torque increased. Based on these results, the increase in nanoparticle concentration in the mixture led to a higher engine torque which is due to the higher energy production as a result of the increased ratio of surface/volume of nanoparticles and the higher thermal conductivity of nano-metallic additives, leading to better fuel evaporation and mixing with air and efficient combustion (Attia et al. 2014). Furthermore, the addition of nanoparticles to conventional diesel fuel shortened the ID which causes complete combustion (Gumus et al. 2016). Additionally, the oxygen content in the molecular structure of nanoparticles entailed a better engine combustion efficiency and caused higher torque values (Mirzajanzadeh et al. 2015). Furthermore, the effect of $Fe_2O_3$ nanoparticles on brake torque was more than $Al_2O_3$ nanoparticles. In this regard, the maximum increase in torque (8.6%) occurred with D+Fe90 fuel blend, while the minimum increase (4.7%) belonged to D+Al30 mixture compared to pure diesel fuel. Compared to the other papers, Gumus et al. (2016) concluded that the engine torque and power were increased by 1% and 3.3%, respectively with the use of Aluminum oxide and copper oxide nanoparticle diesel fuel.

*3.4 Effect of nanoparticle on brake power*

Engine brake power is a function of brake torque and engine rotational speed. Therefore, the maximum engine power is directly related to engine rotational speed. Figure 11 shows the power values of the engine versus rotational speed concerning different nanoparticle-diesel fuel blends based on the engine tests.

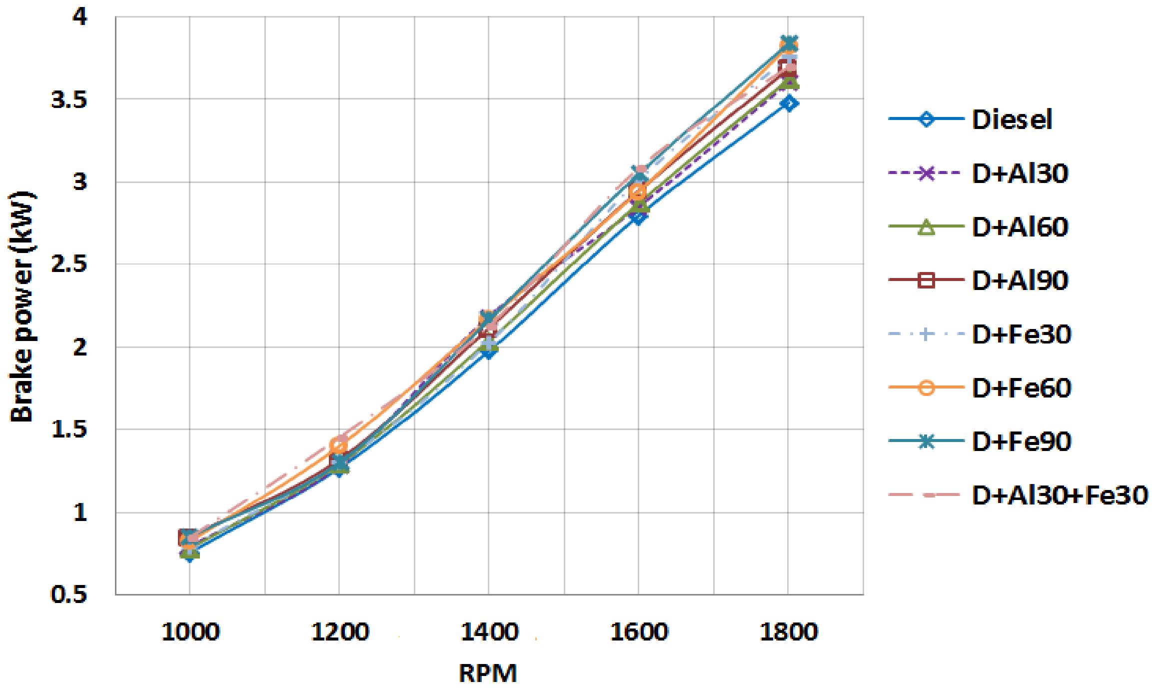


Figure 11: Brake power values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

As seen, the addition of nanoparticles in the fuel blend resulted in better combustion conditions and increased brake power, which is due to the lower ID of fuel blends included in the nanoparticles. Additionally, the oxygen buffer property of nanoparticles releasing oxygen molecules caused an increase in combustion efficiency (Gumus et al. 2016) and the higher thermal conductivity and large ratio of surface/volume enhanced cylinder pressure, resulting in a higher brake power (Sivakumar et al. 2018).

Based on the results, similar to engine brake torque, the D+Fe90 fuel blend entailed the highest increase in brake power (7.08%), while the D+Al30 blend led to the minimum improvement in brake power (4.39%) compared to the pure diesel fuel. Figure 11 also shows that for all blends, the increase in engine rotational speed (1000 rpm to 1800 rpm) predictably resulted in higher engine power. However, some other authors reported that the brake power increased by 3.85% (Patel et al. 2017) and 3.67% (Hosseini et al. 2017) with utilizing the nanoparticle additives.

D+Fe90 fuel mixture generated the highest engine power at all engine rotational speeds compared to other fuel blends. The maximum brake power (3.84 KW) also belonged to this fuel blend occurring at 1800 rpm. Furthermore, pure diesel fuel produced the minimum amount of power at all rotational speeds, hence the minimum brake power (0.7KW) at the rotational speed of 1000 rpm.

*3.5 Effect of nanoparticles on BSFC*

Figures 12 and 13 show the variations of brake specific fuel consumption (BSFC) versus rotational speed (rpm) for various fuel blends at 50% and full engine load, respectively.

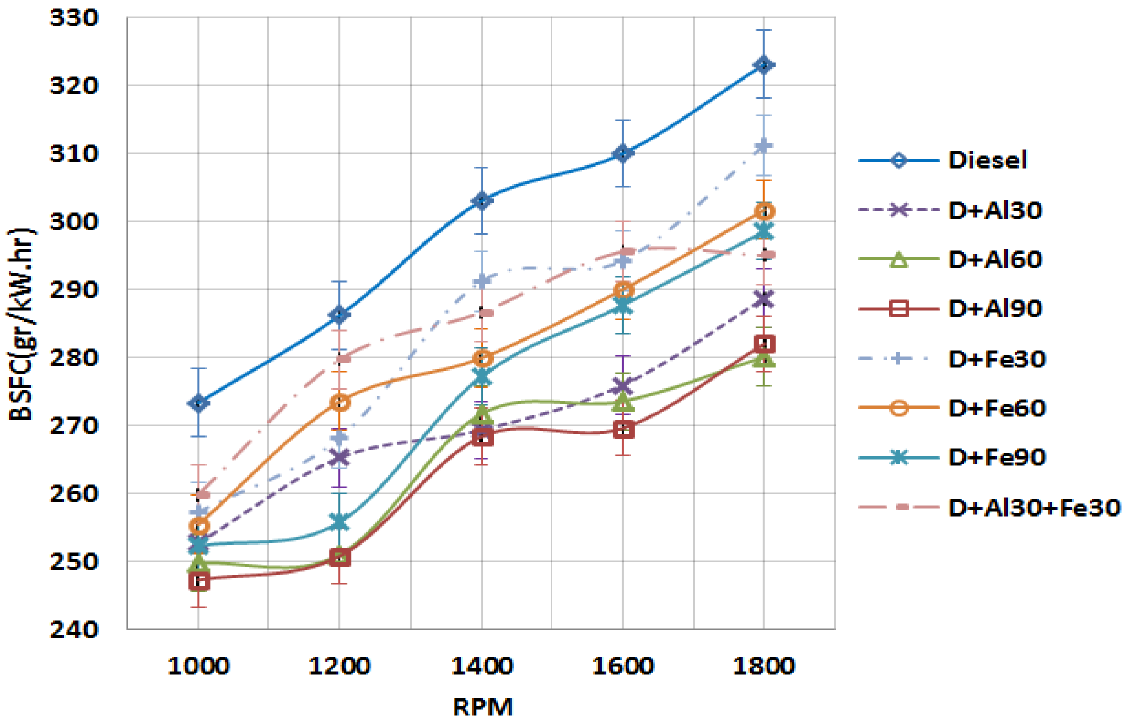


Figure 12: BSFC values versus rotational speed for various fuel blends at 50% engine load

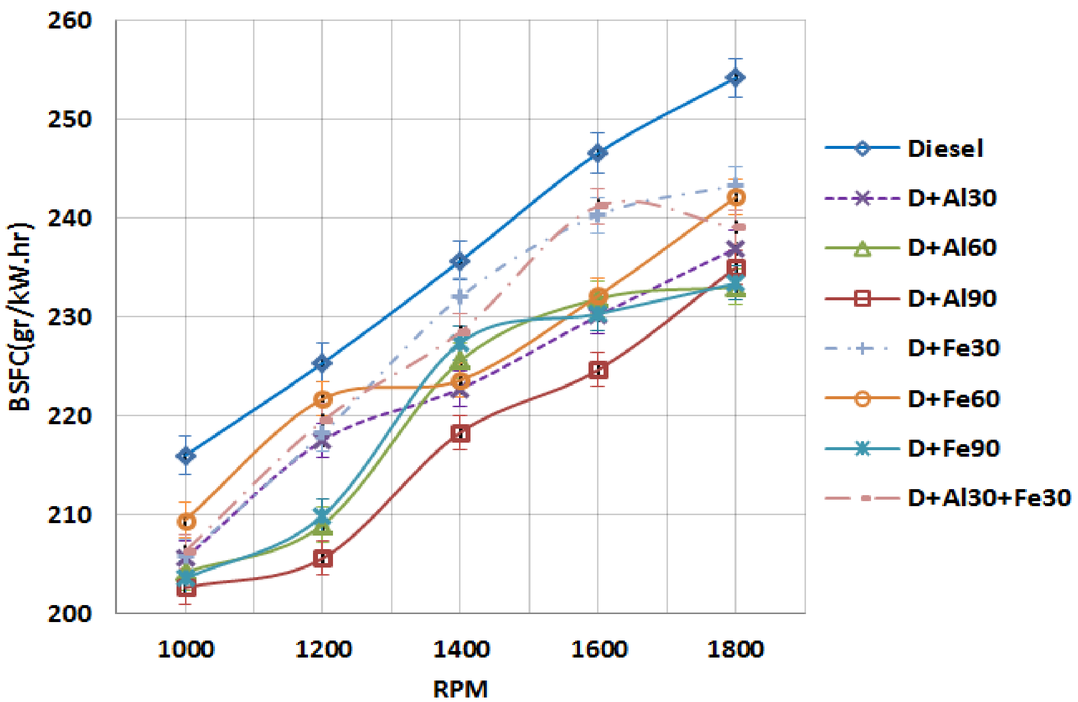


Figure 13: BSFC values versus rotational speed for various fuel blends at full engine load

Based on the results, using aluminum oxide and iron (III) oxide nanoparticles caused a significant decrease in BSFC. Given that BSFC is directly related to brake power and combustion efficiency, the oxygen content in the blend by nanoparticles enhances the combustion efficiency and consequently improves BSFC (Hosseinzadeh Samani et al. 2020). Moreover, nanoparticles have activity as a catalyst and provide oxygen to accelerate combustion(Arul Mozhi Selvan et al. 2014). These additives also enhance the combustion parameters as a result of their large ratio of surface/volume; therefore the brake specific fuel consumption is improved (Shaafi and Velraj 2015)

Based on the results, $Al_2O_3$ nanoparticles were more effective than iron (III) oxide nanoparticles as far as BSFC reduction is concerned which could be because alumina nanoparticles cause higher fuel atomization and more complete combustion. Moreover, the higher density of $Al_2O_3$ fuel blends compared with $Fe_2O_3$ fuel blends produced a higher brake power for the same volume of fuel injected into the combustion chamber, hence the reduction in BSFC. According to the results, the BSFC decreased with increasing the load applied on the engine for all fuel blends owing to the higher combustion temperature which results in better combustion conditions and produces higher brake power(Shirneshan et al. 2014). D+Al90 and D+Fe30 fuel blends had the maximum (8.2%) and minimum (4.3%) decrease in BSFC in comparison with D100, respectively. However, some other authors reported 1.2%(Gumus et al. 2016), 12%(El-Seesy et al. 2018), and 6% (Aalam et al. 2015) reduction in BSFC for diesel engine fuelled with nanoparticle additives.

Based on the results, the minimum BSFC (203 g/kW.h) occurred in D+Al90 blend at the speed of 1000 rpm, and the highest BSFC (254 g/kW.h) belonged to neat diesel fuel at 1800 rpm under full engine load. Besides, the D+Al90 blend had the minimum BSFC (247 g/kW.h) at the speed of 1000 rpm and the maximum BSFC (323 g/kW.h) belonged to neat diesel fuel at 1800 rpm under 50% engine load.

*3.6 Effect of nanoparticles on brake thermal efficiency*

Brake thermal efficiency (BTE) is defined as the ratio of mechanical energy (output energy) to the chemical energy (input). The BTE values versus rotational speed for different fuel blends under 50% and full engine loads are shown in Figures 13 and 15, respectively.

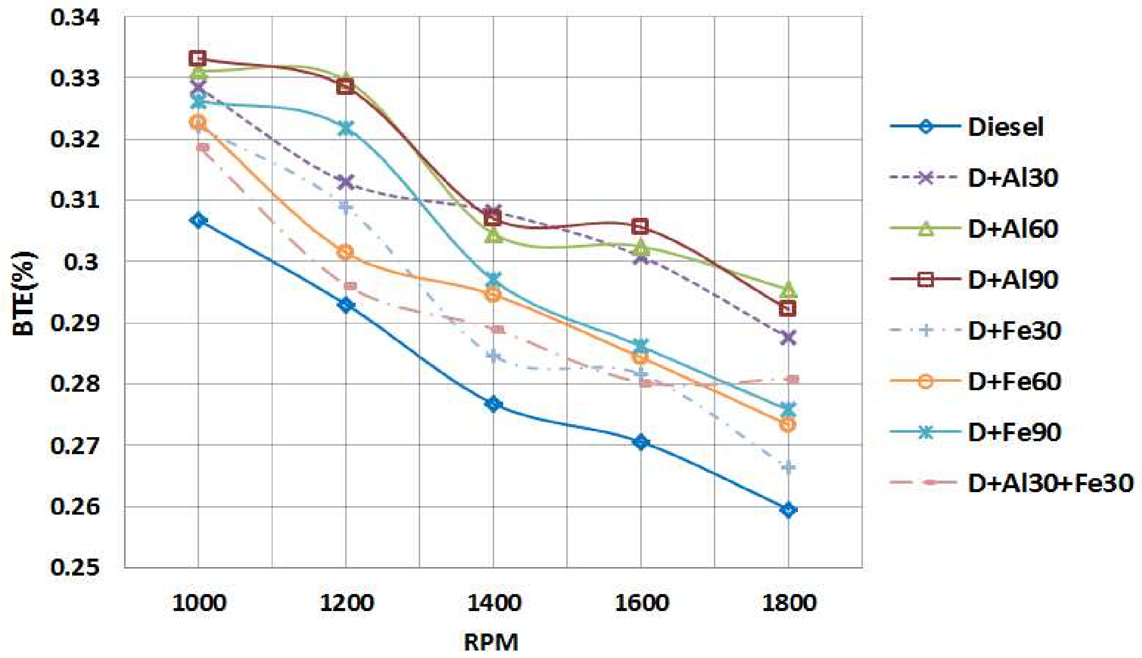


Figure 14: BTE values versus rotational speed for different nanoparticle-diesel fuel blends at 50% engine load

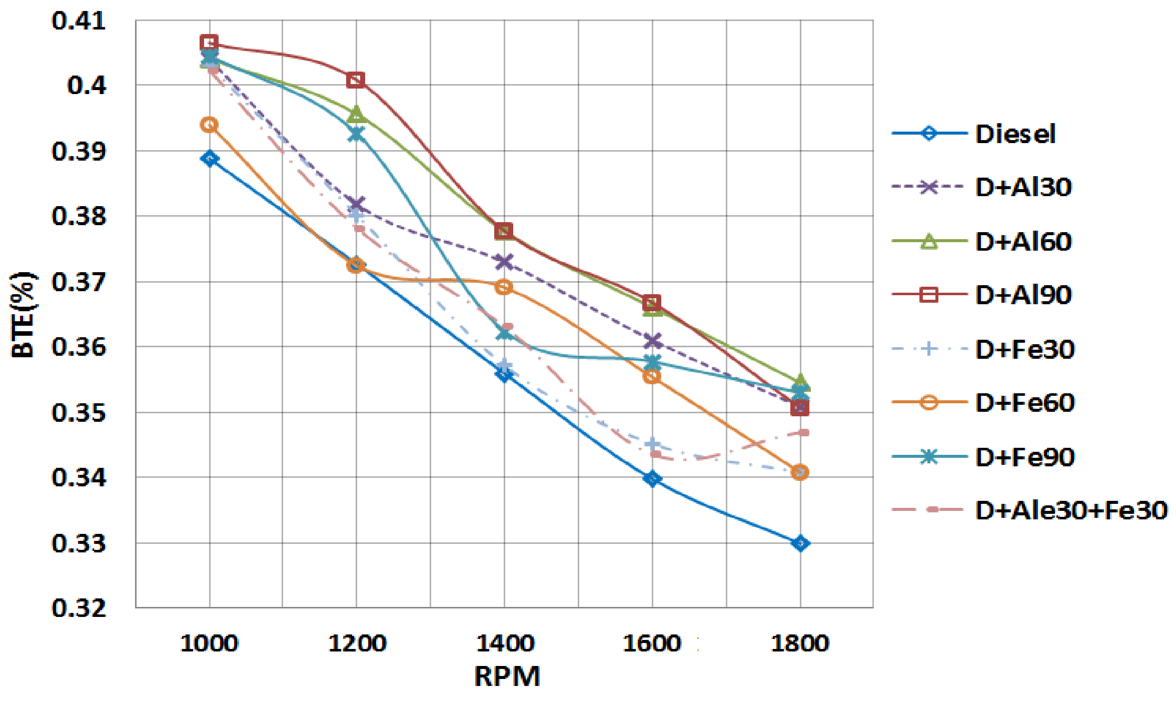


Figure 15: BTE values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

Aluminium oxide and iron (III) oxide nanoparticles resulted in a significant improvement in BTE. Given that BTE is inversely related to the BSFC and LHV of the fuels and is mostly influenced by BSFC, the improvement in the fuel economy of the blends entailed a better thermal efficiency. Moreover, the enhanced ratio of the surface/volume of the nanoparticles favouring better combustion and resulted in improved brake thermal efficiency (Basha and Anand 2011; Prabu and Anand 2016).

Based on the results, $Al_2O_3$ nanoparticles were more effective than $Fe_2O_3$ nanoparticles in producing higher brake thermal efficiency probably because of the lower BSFC of $Al_2O_3$ fuel blends resulting in higher BTE. D+Al90 and D+Fe30 fuel blends had the maximum (6.6%) and minimum (3%) improvement in BTE compared to neat diesel fuel, respectively. Although other researchers obtained 18.8% (Chen et al. 2018), 2.5% (Aalam et al. 2015), 17.9% (Shaafi and Velraj 2015) and 9% (Attia et al. 2014) improvement in BTE with the addition of nanoparticles in diesel fuel.

*3.7 Effect of nanoparticles on exergy efficiency*

Figure 16 shows the impact of fuel blends on the exergy efficiency of the engine at various engine speeds and full load.

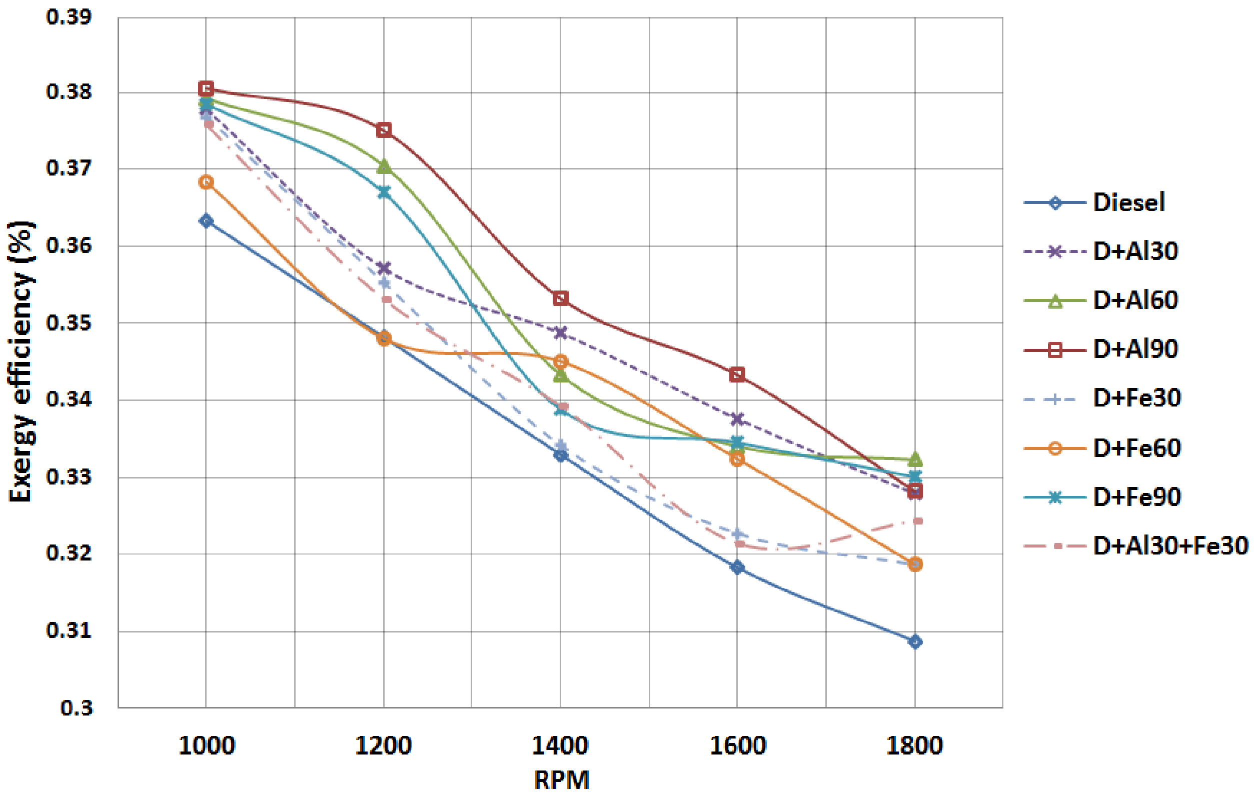


Figure 16: Exergy efficiency values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

Similar to BTE, $Al_2O_3$ nanoparticle fuel blends had a higher exergy efficiency compared to $Fe_2O_3$ nanoparticles which is probably due to the lower BSFC of $Al_2O_3$ fuel blends increasing the energy efficiency. According to the results, neat diesel had the lowest value (30.8%) of exergy efficiency. Moreover, the maximum exergy efficiency (38%) belonged to the D+Al90 fuel blend while the minimum exergy efficiency (31.9%) occurred in D+Fe30 among all fuel blends with nanoparticle additives. Furthermore, the exergy efficiency dropped with increasing engine speed because of the sharp rise in BSFC at higher rpms.

*3.8 Effect of nanoparticles on CO emission*

Figure 17 shows the impact of fuel blends on the CO emission of the engine. According to the figure, CO emission decreases with increasing the engine load from 25 to 100% (full load) for all fuel blends, because at higher loads, the combustion temperature increases which results in better combustion condition and lower carbon monoxide emission (Shirneshan et al. 2016a, 2016b). The results further showed that with the increase in nanoparticle fraction, CO emission was reduced. High ratio of surface to volume and the catalytic effect of nanoparticles enhance the burning efficiency of fuel blends and reduce CO formation (Sivakumar et al. 2018). Moreover, $Al_2O_3$ and $Fe_2O_3$ addition shortened the ID time which yields inefficient combustion and lower CO production (Motamedifar and Shirneshan 2018). The presence of sufficient active oxygen in nanoparticle additives improved combustion, especially at higher engine loads, and reduced CO emission (Aalam et al. 2015; George et al. 2015). Concerning CO emission reduction, the effect of $Fe_2O_3$ was slightly more than $Al_2O_3$ nanoparticle additives. However, the minimum (8%) and maximum (21%) decrease in CO emission with respect to pure diesel fuel were observed after using D+Fe30 and D+Al90 fuel blends. Moreover, similar conclusions were also drawn by other authors (El-Seesy et al. 2018; Sivakumar et al. 2018). For example, Gumus et al. (2016) reported that the CO emissions decrease by 11% with the addition of $Al_2O_3$ into diesel fuel.

Based on the results, the minimum CO emission (0.88%) belonged to the D+Fe90 blend at full engine load, and the highest amount of CO emission (1.83%) occurred in pure diesel fuel at 25% engine load.

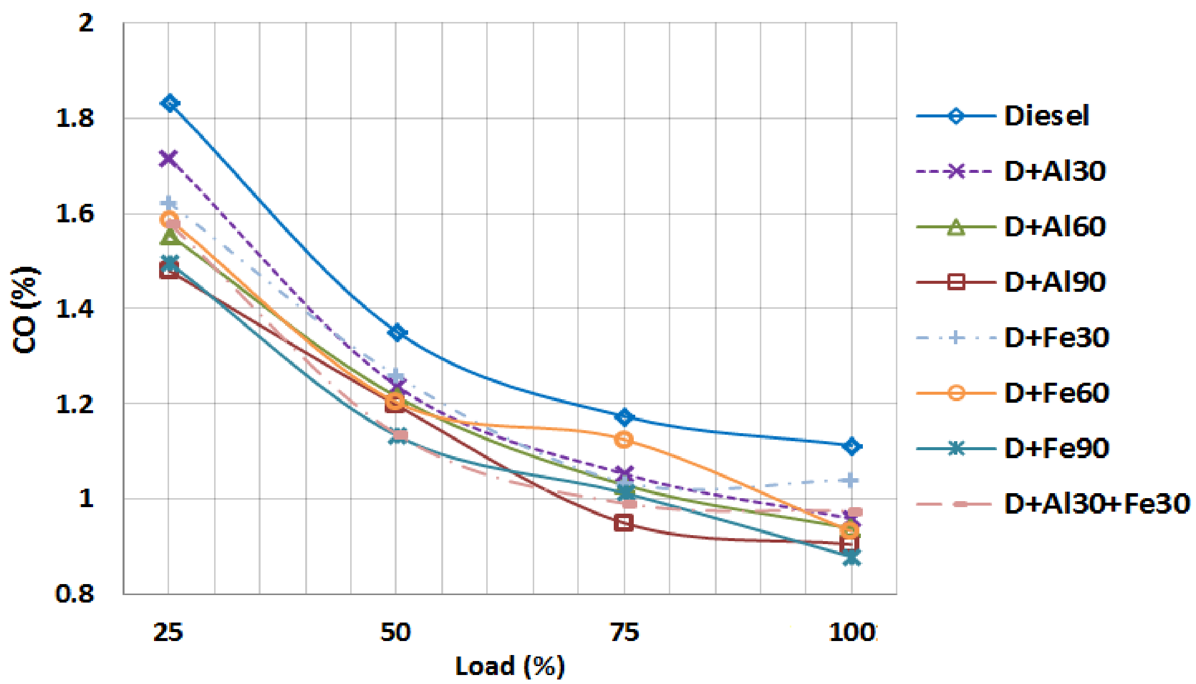


Figure 17: Variations of the CO emission against engine load for different nanoparticle-diesel fuel blends

*3.9 Effect of nanoparticles on NOx emission*

Nitrous oxides in the exhaust gas are contained a mixture of NO and $NO_2$. The oxygen and nitrogen existing in the air react at very high temperatures. Therefore, high temperature and available oxygen are the main parameters for $NO_x$ production. The variations in $NO_x$ emission versus engine load regarding different nanoparticle-diesel fuel blends are shown in Figure 19.

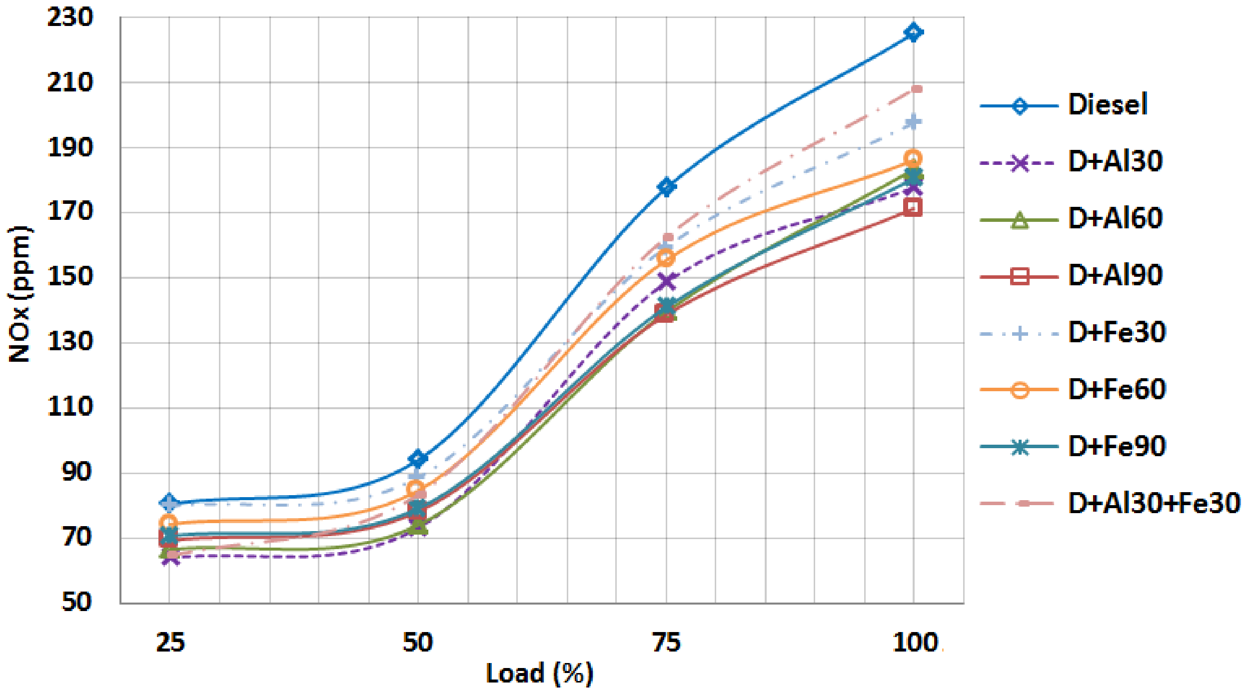


Figure 19: Variations of the $NO_x$ emission versus engine load for different nanoparticle-diesel fuel blends

As seen in this figure, the concentration of $NO_x$ in the exhaust gas of the engine increased at higher engine loads, which is related to the increase in combustion temperature at higher engine loads (Hojati 2019, Salehian 2020). Based on the findings, a significant reduction (20% on average) was observed in $NO_x$ emission following the addition of nanoparticles (especially $Al_2O_3$ nanoparticles) to neat fuel diesel. Similar results were reported by other researchers (El-Seesy et al. 2018, Gumus et al. 2016). However, some authors reported the reverse change in $NO_x$ emission with the addition of nanoparticles in diesel fuel (Shaafi 2015; Sivakumar et al. 2018).

The reason for this reduction is the thermal stability and catalytic activity of fuel blend blends which facilitate reaction completion and form the final products from the HC compounds with a lowest thermal breakdown, causing a reduction in active radicals to form NOx (Sadhik Basha 2013, Sajith et al. 2010). Besides, nanoparticles can scavenge the NO radicals that cause a reduction in NOx for fuel blends with respect to neat diesel (Dowding et al. 2012). Also, NOx formation is related to the nitrogen oxidation at the highest combustion temperature (Vairamuthu et al. 2016). Therefore, neat diesel with a prolonged ignition delay provided a greater chance for

the formation of a premixed mixture and higher peak combustion temperature compared with nano fuels and produces higher NOx formation (Lee and Bae 2011).
The results also showed that the NOx emission of $Fe_2O_3$ nano fuels is higher than that of $Al_2O_3$ nano fuels. The reason is related to the advanced combustion phasing for $Fe_2O_3$ nano-fuels that causes higher combustion temperature and resulted in higher NOx formation.
According to the results, the D+Fe30+AL30 fuel blend did not significantly improve $NO_x$ emission compared to other fuel blend blends, particularly at higher loads. This is because of the higher portion of the premixed burn phase combustion of this fuel which enhances the combustion temperature and NOx emissions (Aalam et al. 2015; Shaafi 2015).
Findings also showed that neat diesel fuel produced the maximum amount of $NO_x$ emission (225ppm) at full engine load, while the minimum amount of $NO_x$ emission (63.8ppm) belonged to D+Al30 at 25% engine load.

### *3.10 Effect of nanoparticles on $SO_2$ emission*

Sulfur oxides are produced as a result of the reaction between sulfur content of diesel fuel and oxygen. However, even low amounts of $SO_2$ in the exhaust gas are produced from the combustion of the sulfur content of the fuel. Sulfur oxides ensue corrosion in engine parts, and their emission to the atmosphere leads to pollution and acid rain (Pulkrabek 1997; Tikhomirov et al. 2006).
Based on the results (Figure 19), $SO_2$ concentration in the exhaust gas increased at higher engine loads possibly due to the thermal breakdown of the sulfur compounds in the fuel, causing $SO_2$ formation (Nedayali 2016).
The results further showed that with increasing the fraction of nanoparticles in the fuel blend, the emission of $SO_2$ pollutant was reduced. Similarly, some other authors also reported that the $SO_2$ emission decreased with the addition of nanoparticles to neat diesel (Karthikeyan 2016; Sabet Sarvestany et al. 2014).
Based on the results, the lowest amount of $SO_2$ emissions was observed in D+Al90 and D+Fe90 fuel blends. This reduction originates from the high ratio of surface to volume and catalytic properties of nanoparticles that enhance the combustion efficiency of fuel blends and reduce $SO_2$ (El-Seesy et al. 2018; Sivakumar et al. 2018). Moreover, $Al_2O_3$ and $Fe_2O_3$ addition reduced the ignition delay time, resulting in better combustion and lower $SO_2$ production (Gumus et al. 2016).
The findings also revealed that the influence of $Fe_2O_3$ nanoparticle was more than aluminum oxide nanoparticle as regards reducing $SO_2$ emissions.
The highest amount of $SO_2$ emission (39.1ppm) was seen in neat diesel fuel at full load while the lowest (9.6ppm) occurred at 25% engine load in the D+Al90 fuel blend.

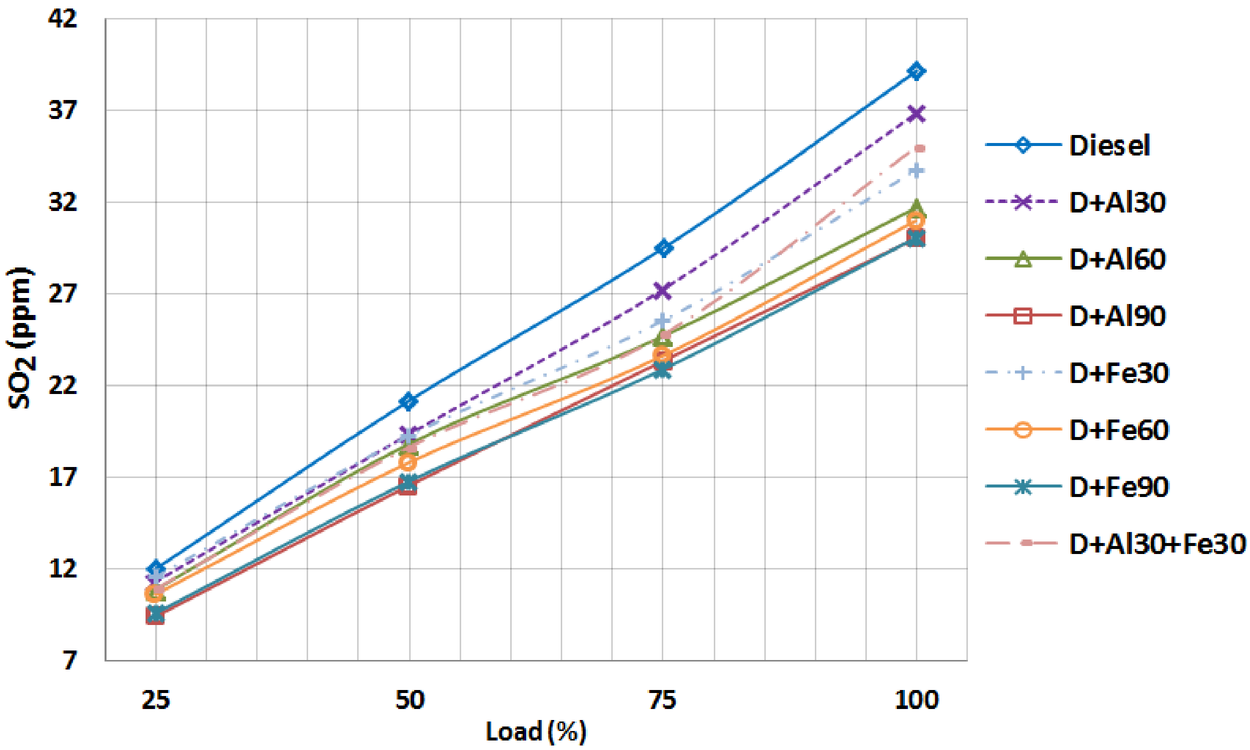


Figure 19: Variations of the $SO_2$ emission against engine load for different nanoparticle-diesel fuel blends

*3.11 Cost analysis*

Table 5 shows the cost analysis of using nanoparticles with diesel fuel in the CI engine. According to the results, the BSFC decreased following the addition of nanoparticles in neat diesel and led to lower fuel consumption. Table 5 presents the calculations of reduction in fuel consumption and cost saving per 1000 kWh output energy from the engine at 1800 rpm under full load. The diesel fuel price was considered as 0.78 US Dollars per litre. Also, the price of 1 kg $Al_2O_3$ and $Fe_2O_3$ nanoparticles (US Research Nanomaterials Inc.) were 185 and 348 US Dollars, respectively. Although the addition of nanoparticles to conventional diesel fuel increased the fuel cost, the results indicated that there is still room for fuel consumption cost savings of approximately 7 to 17 US Dollars per 1000 kWh output energy from the engine by use of nanoparticles. For example, the BSFC for the D+Al30+Fe30 blend is 239 g/kW.h and for neat diesel is 255 g/kW.h at 1800 rpm under full load. Therefore, for 1 kWh output energy at the same conditions, there is around 16 gr or 19 cc reduction in fuel consumption which means the cost of 0.0145 US Dollars. However, the mass of nanoparticles used will be 0.01434 gr at this condition which means the cost of 0.00382 US Dollars. Thus, the calculation for 1000 kWh output energy shows approximately 11 US Dollars cost saving.

Table 5: Cost analysis results

| Fuel | Reduction in the fuel consumption per 1 kWh output energy compared to neat diesel(gr) | Reduction in fuel consumption per 1 kWh output energy compared to neat diesel (lit) | Mass of consumed nanoparticles (gr) | Cost of nanoparticles addition in neat diesel ($) | Cost saving compared to neat diesel ($) per 1 kWh output energy |
|---|---|---|---|---|---|
| D+Al30 | 17.24 | 0.0211 | 0.0071 | 0.0013 | 0.01517 |
| D+Al60 | 21.13 | 0.0259 | 0.0139 | 0.0026 | 0.01761 |
| D+Al90 | 19.19 | 0.0235 | 0.0211 | 0.0039 | 0.01443 |
| D+Fe30 | 10.84 | 0.0133 | 0.0072 | 0.0025 | 0.00782 |
| D+Fe60 | 12.04 | 0.0148 | 0.0145 | 0.0050 | 0.00646 |
| D+Fe90 | 20.76 | 0.0254 | 0.0210 | 0.0073 | 0.01254 |
| D+Al30+Fe30 | 15.13 | 0.0186 | 0.0072Al<br>0.0072Fe | 0.0038 | 0.01064 |

## 4. Conclusion

In this research, the engine tests were performed to evaluate the effect of using $Fe_2O_3$ and $Al_2O_3$ nanoparticle additives with fractions of 30, 60 and 90 ppm on the performance (brake power, torque, BSFC) and emission (CO, $NO_x$, and $SO_2$) characteristics of a CI engine. The most important findings of this study are:

- In general, fuel blends and higher amounts of nanoparticles in fuel mixture increased the power and torque (up to 8%) and reduce BSFC (up to 9%) compared to neat diesel fuel at all rotational speeds owing to the shorter ID, oxygen addition to the blend, high ratio of surface/volume and better thermal conductivity which increases the combustion efficiency.
- The peak combustion pressure increased by 4% and the HRR was improved by 15% with respect to neat diesel with nanoparticles addition. Moreover, the rate of pressure rise increased by 18% in comparison with neat diesel with nano-metallic additives.
- D+Fe90 blend has the highest combustion pressure and the maximum HRR among other fuel blends.
- The effect of $Fe_2O_3$ nanoparticles on brake power and brake torque is more than aluminum oxide ($Al_2O_3$) nanoparticles. On the other hand, $Al_2O_3$ nanoparticles showed better results in reducing BSFC and producing higher brake thermal efficiency compared with that of $Fe_2O_3$ nanoparticle additives.
- BTE was improved by 14% following the addition of nanoparticles.
- Similar to brake thermal efficiency, $Al_2O_3$ nanoparticle fuel blends, owing to their lower BSFC, have a higher exergy efficiency compared to $Fe_2O_3$ nanoparticles.
- With the increase in nanoparticle concentration, CO emission was reduced by 21%.
- $Fe_2O_3$ is slightly more effective than $Al_2O_3$ nanoparticle additives as far as reduction in CO emission is concerned.
- There was a significant reduction (up to 24%) in $NO_x$ emission by addition of nanoparticles (especially $Al_2O_3$) to neat fuel diesel owing to the thermal stability and catalytic behavior of fuel blends reducing the active radical to form NOx.
-At higher fractions of nanoparticles, the emission of $SO_2$ pollutant decreased (up to 23%) and the lowest amount of $SO_2$ emissions was observed in D+Al90 and D+Fe90 fuel blends.

-The influence of $Fe_2O_3$ nanoparticle is more than $Al_2O_3$ nanoparticle in terms of reducing $SO_2$ emission.
- The cost analysis results indicated that the fuel consumption cost can be saved by about 7 to 17 US Dollars per 1000 kWh output energy with the use of nanoparticles.
- Generally, both nanoparticle additives improved the combustion parameters and performance and emission characteristics of the engine. Also, $Fe_2O_3$ nanoparticle additives have better results regarding the engine combustion and performance compared with $Al_2O_3$ nanoparticle additives. On the other hand, the addition of $Al_2O_3$ nanoparticle to pure diesel can improve further the emission characteristics of the engine and fuel cost. Overall, the $Fe_2O_3$-$Al_2O_3$ hybrid fuel blend is preferred if the performance and emission characteristics of the engine are both considered.
- The effect of fuel blends on unburned hydrocarbon and particulate matter (PM) emissions, the impact of using higher concentrated nanoparticle-diesel fuel blends, and the effect of using nanoparticle biofuels are proposed for future studies.

## Declarations

## Conflict of interest statement

The authors state that there is no conflict of interest.

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## Appendix 1

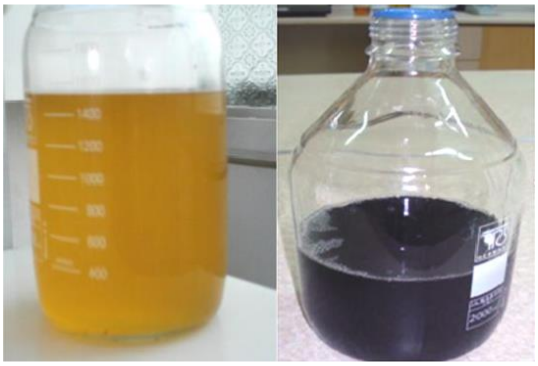


Figure A1: $Al_2O_3$ (left) and $Fe_3O_4$ (right) nanoparticle-diesel fuel blends

Table A1: Properties of nanoparticle-diesel fuel blends

| Property | unit | Range | Method | D+ Fe30+AL30 | D+ Fe90 | D+ Fe60 | D+ Fe30 | D+ AL90 | D+ AL60 | D+ AL30 | Diesel fuel |
|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Flash point | °C | 52< | D93 | 64 | 67 | 64 | 63 | 69 | 67 | 66 | 58 |
| Cloud point | °C | - | D2500 | -4 | -5 | -4 | -4 | -6 | -6 | -5 | -3 |
| Kinematic viscosity (40℃) | $Mm^2/s$ | 1.9-4.1 | D445 | 3.6 | 3.8 | 3.7 | 3.6 | 3.9 | 3.8 | 3.6 | 3.5 |
| Density | $g/cm^3$ | - | D4052 | 0.820 | 0.823 | 0.821 | 0.817 | 0.827 | 0.825 | 0.824 | 0.816 |
| Heating value | kJ/kg | - | D 3338 | 43453 | 43729 | 43657 | 43442 | 43685 | 43502 | 43365 | 42929 |
| Cetane number | - | - | D613 | 55.2 | 56.4 | 55.9 | 55.3 | 55.6 | 55.3 | 54.7 | 51 |

# Figures

**Figure 1**

The engine test set-up

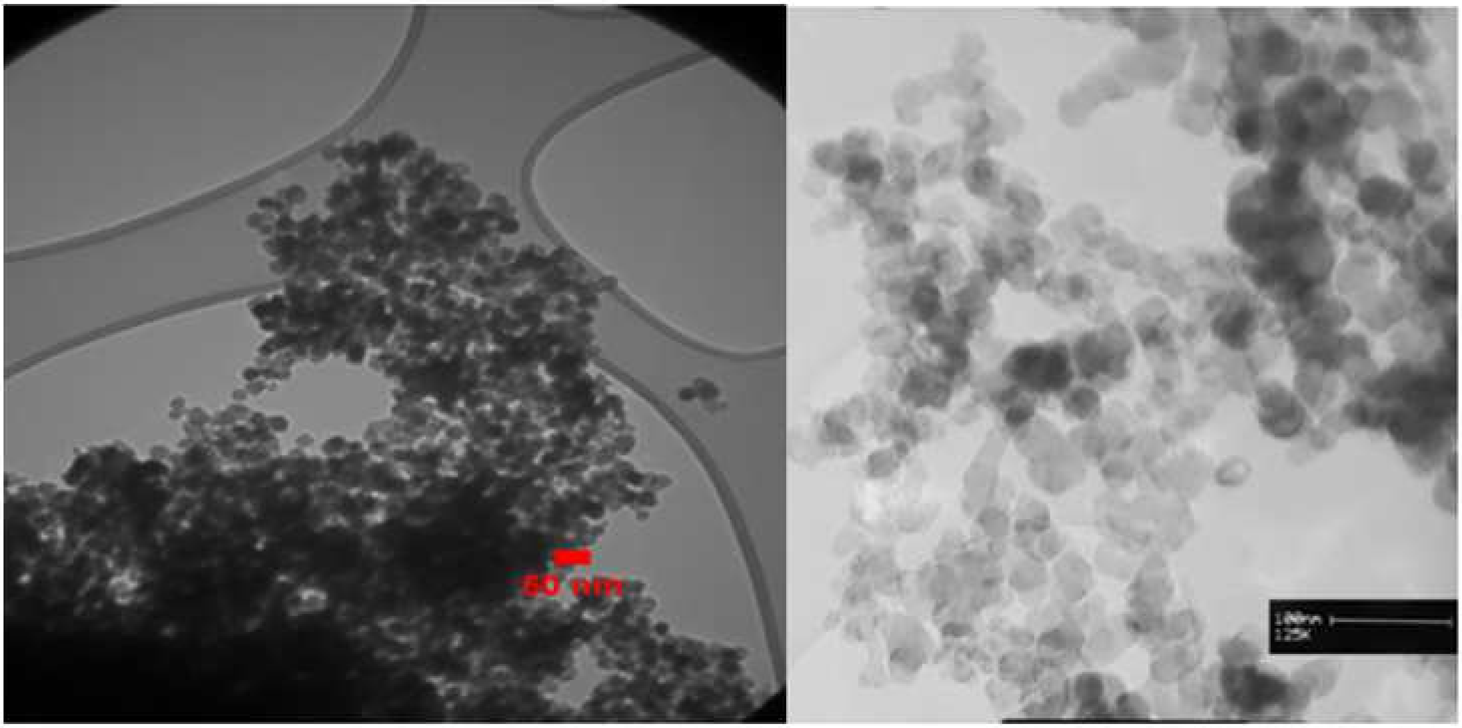



**Figure 2**

TEM and SEM analysis of Al2O3 nanoparticles

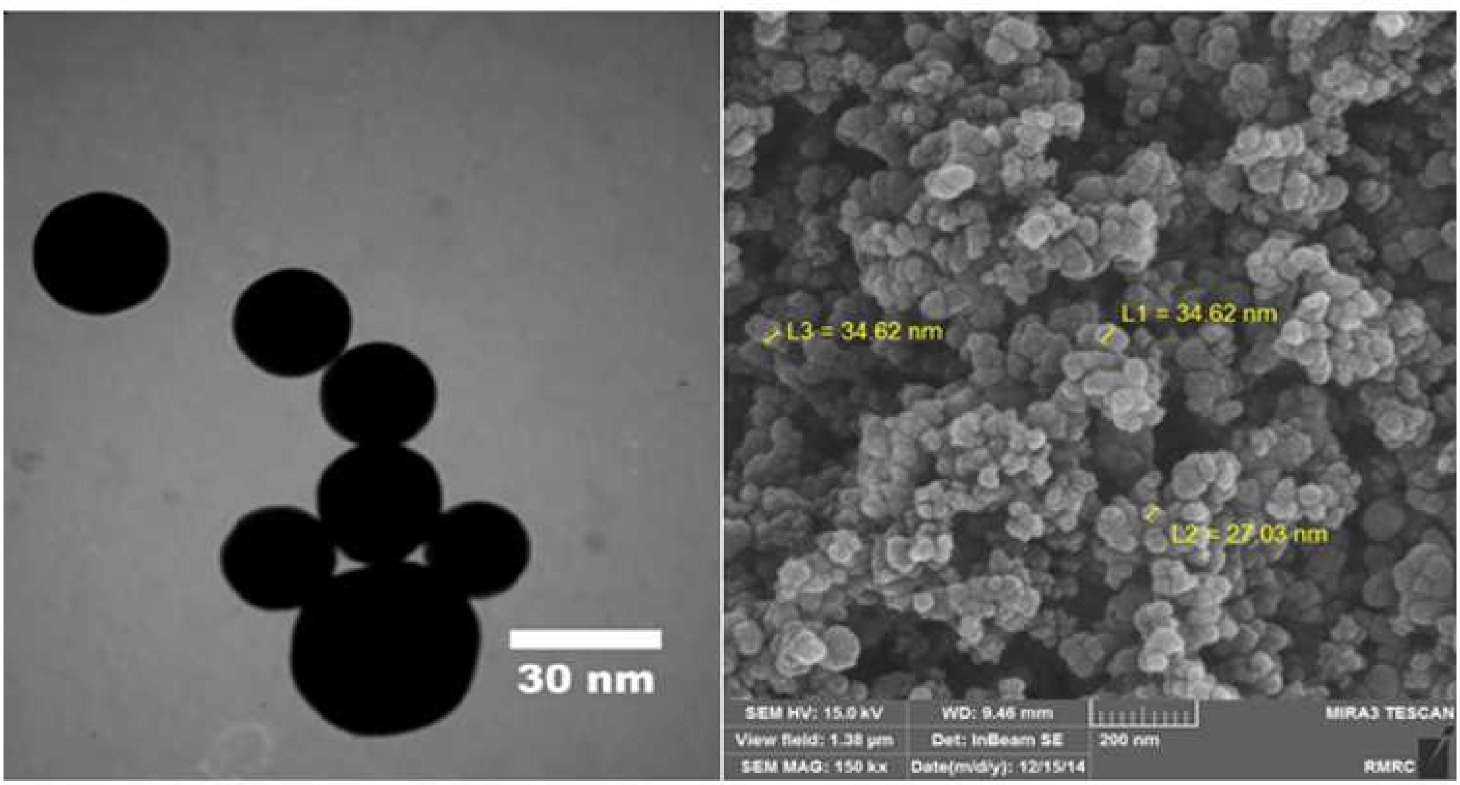
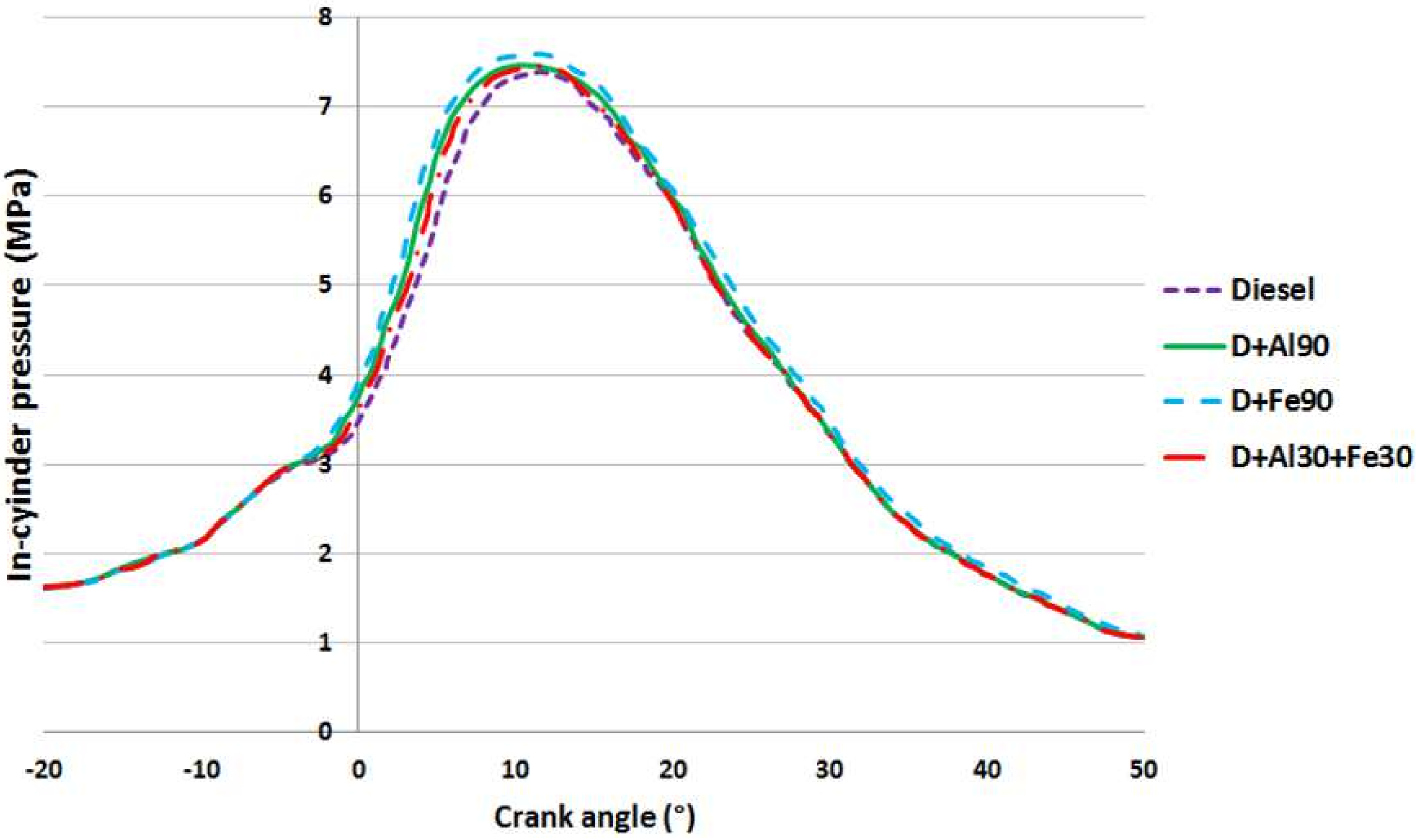



**Figure 3**

TEM and SEM analysis of Fe2O3 nanoparticles




## Figure 4

In-cylinder pressure variations versus crank angle at 50% engine load

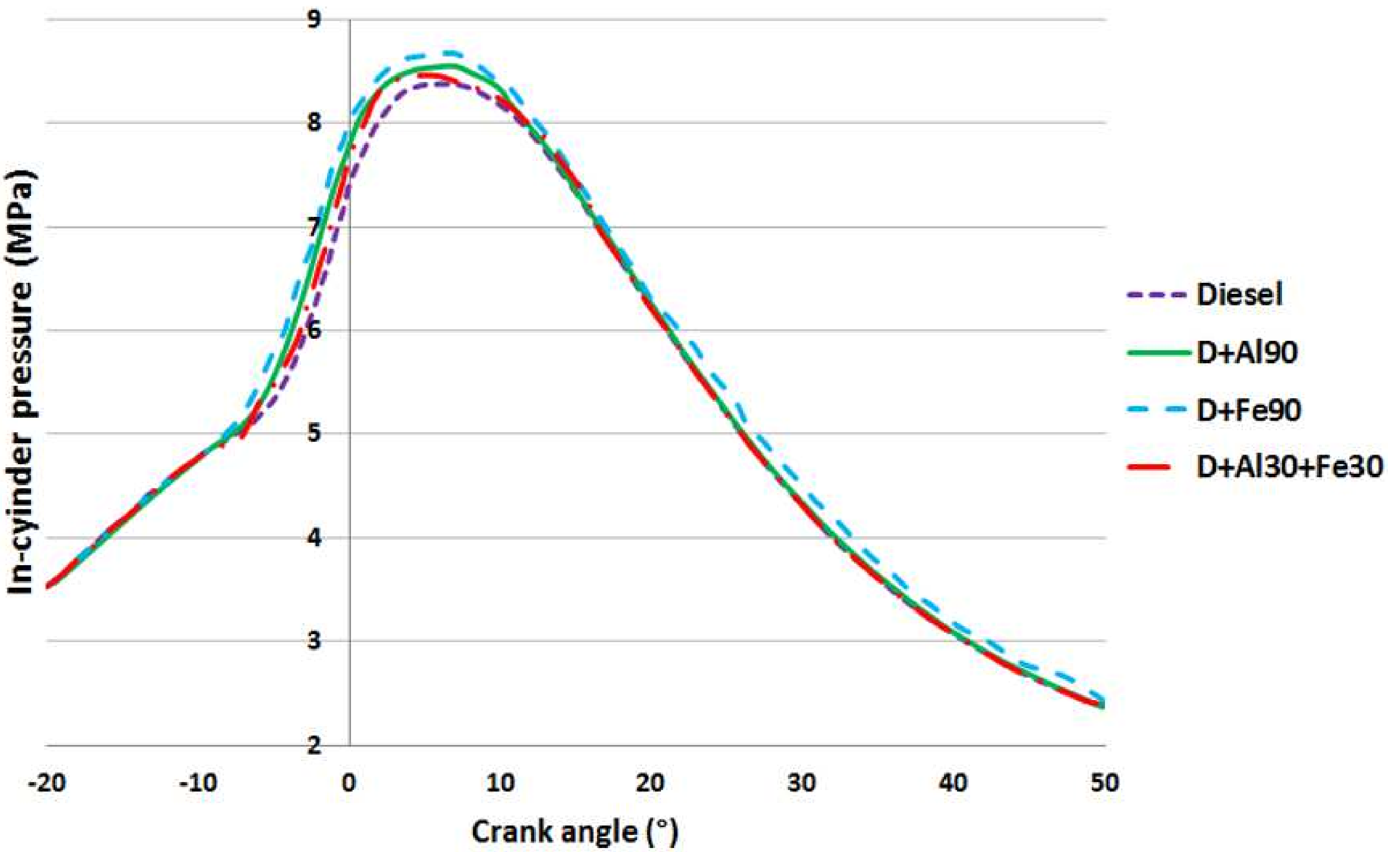
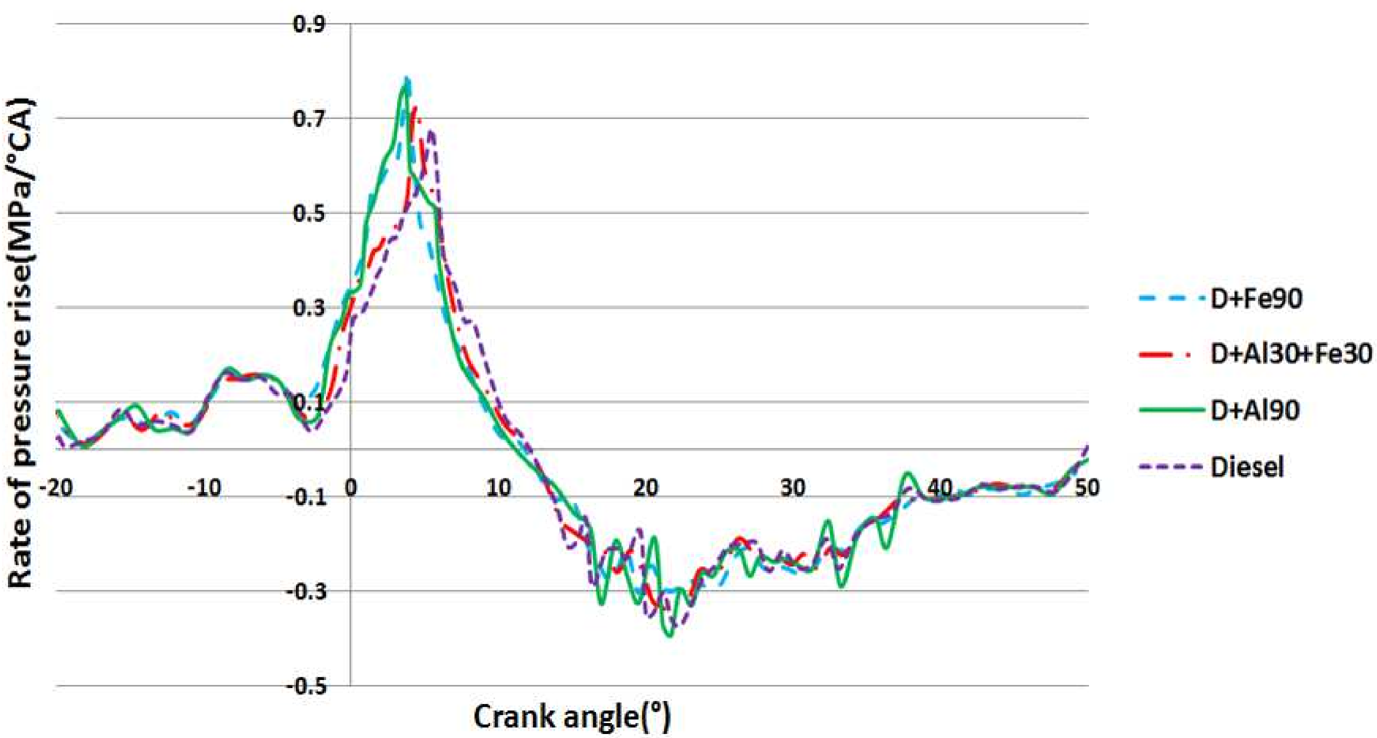


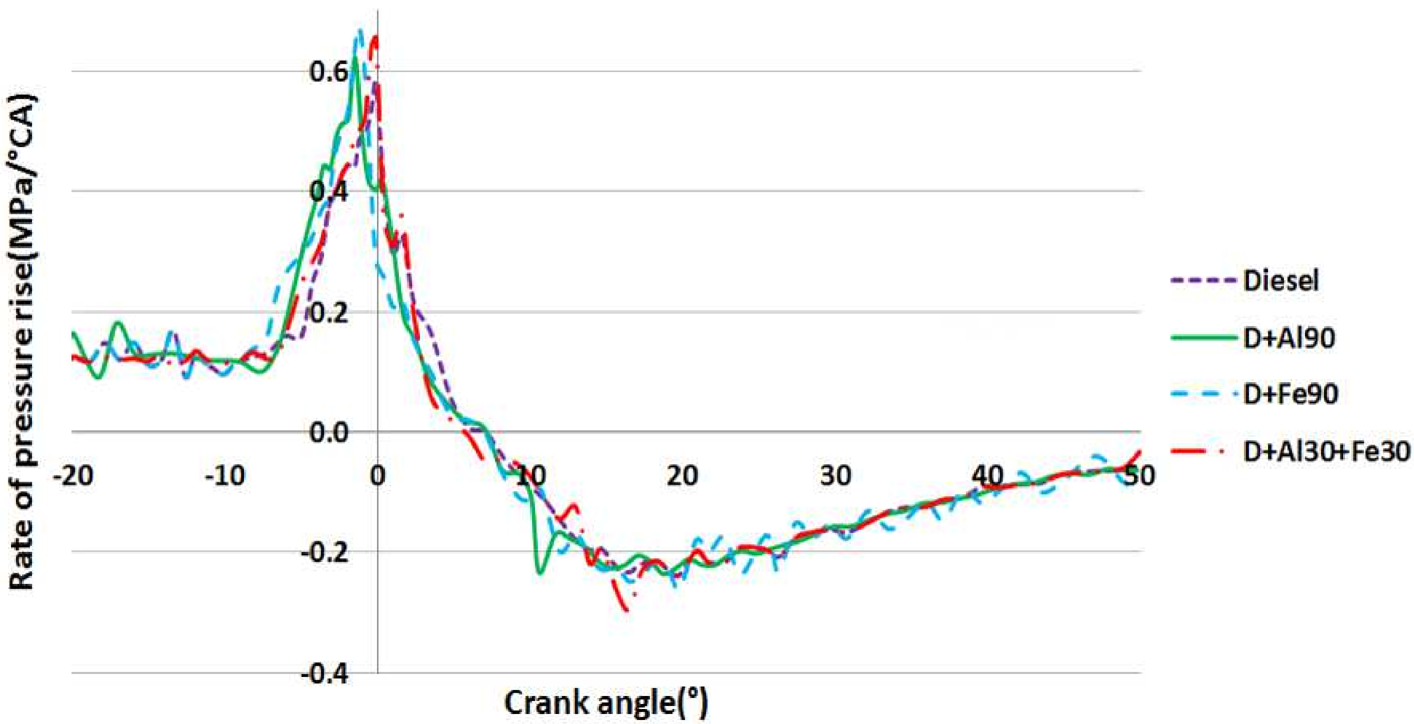

Figure 5

In-cylinder pressure variations versus crank angle at full engine load



## Figure 6

Variations of the rate of pressure rise against crank angle at 50% engine load




## Figure 7

Variations of the rate of pressure rise against crank angle at full engine load

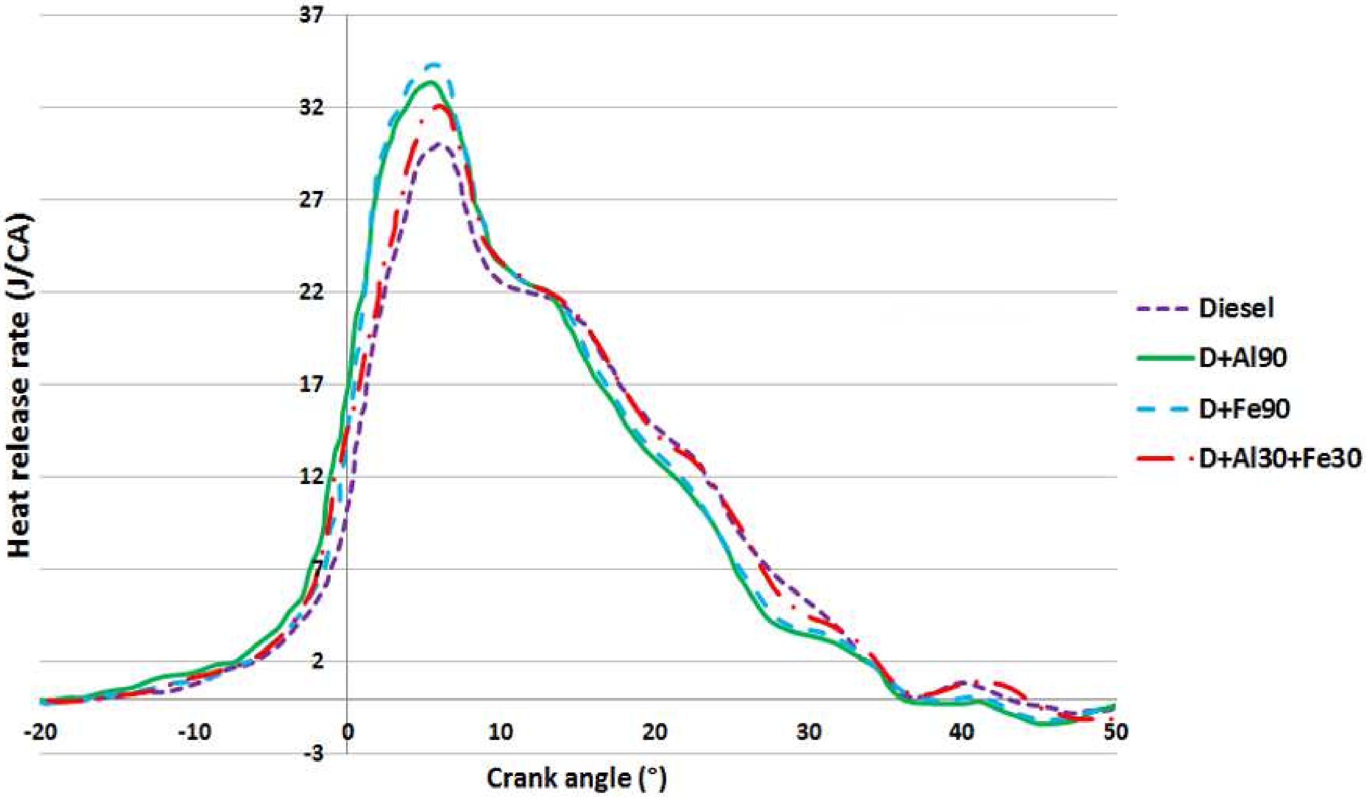



Figure 8

Variations of the HRR versus crank angle at 50% engine load

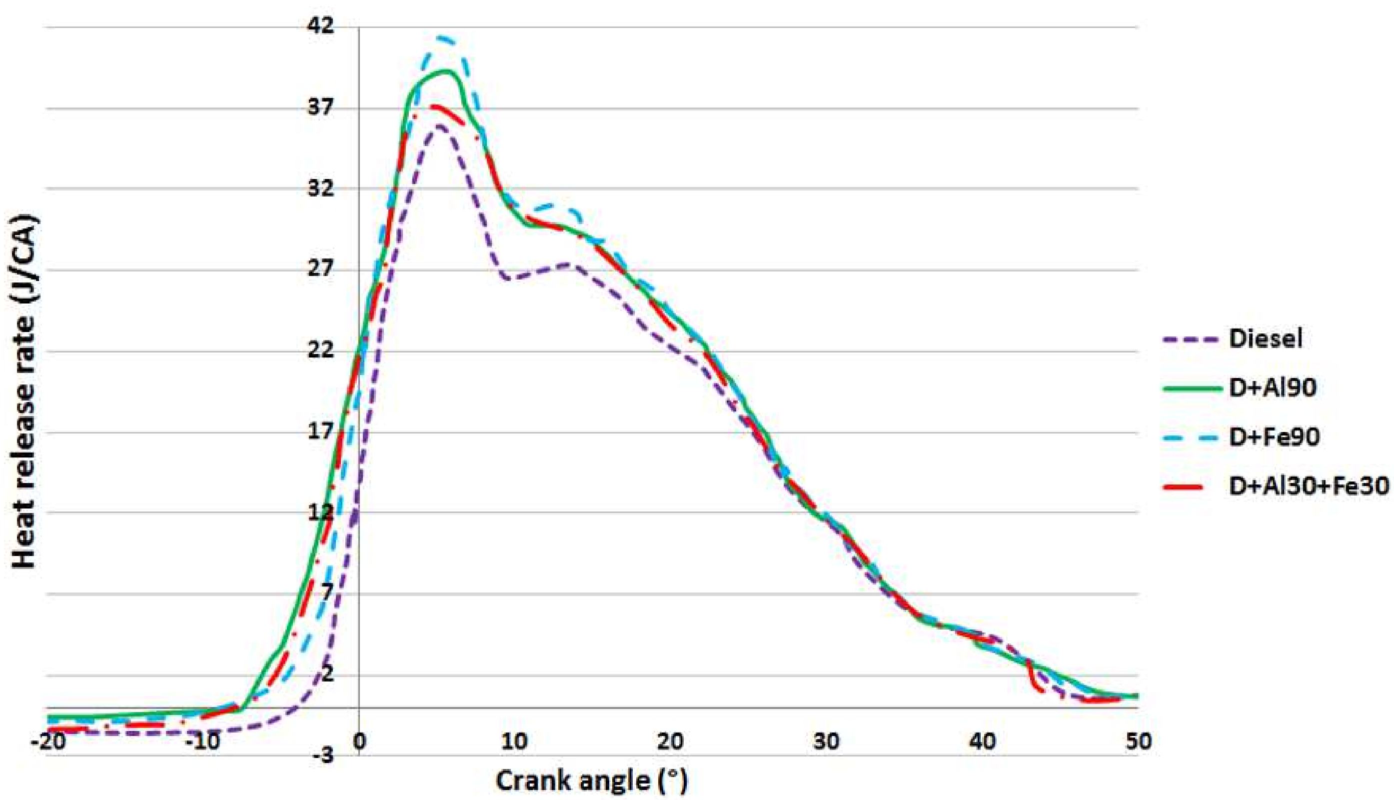


Figure 9

Variations of the HRR versus crank angle at full engine load

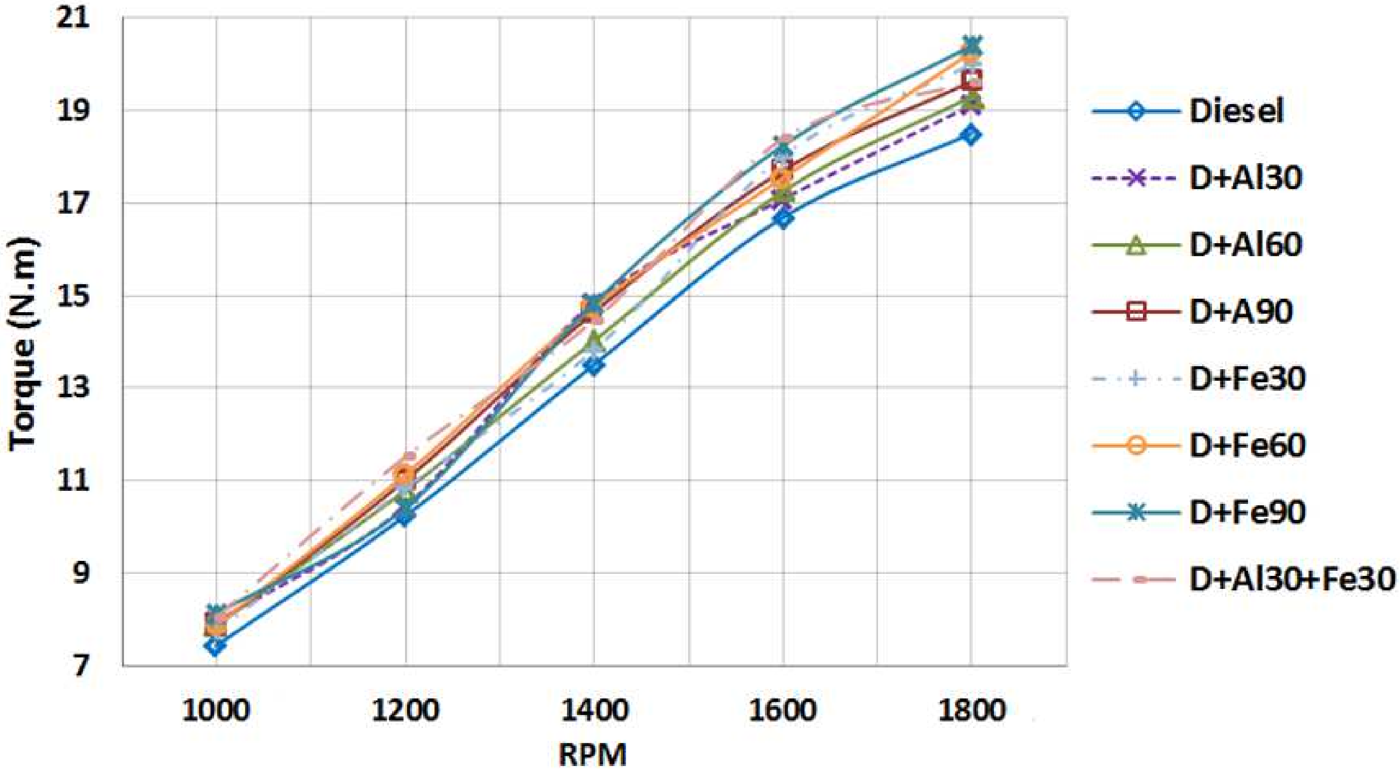



Figure 10

Brake torque values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

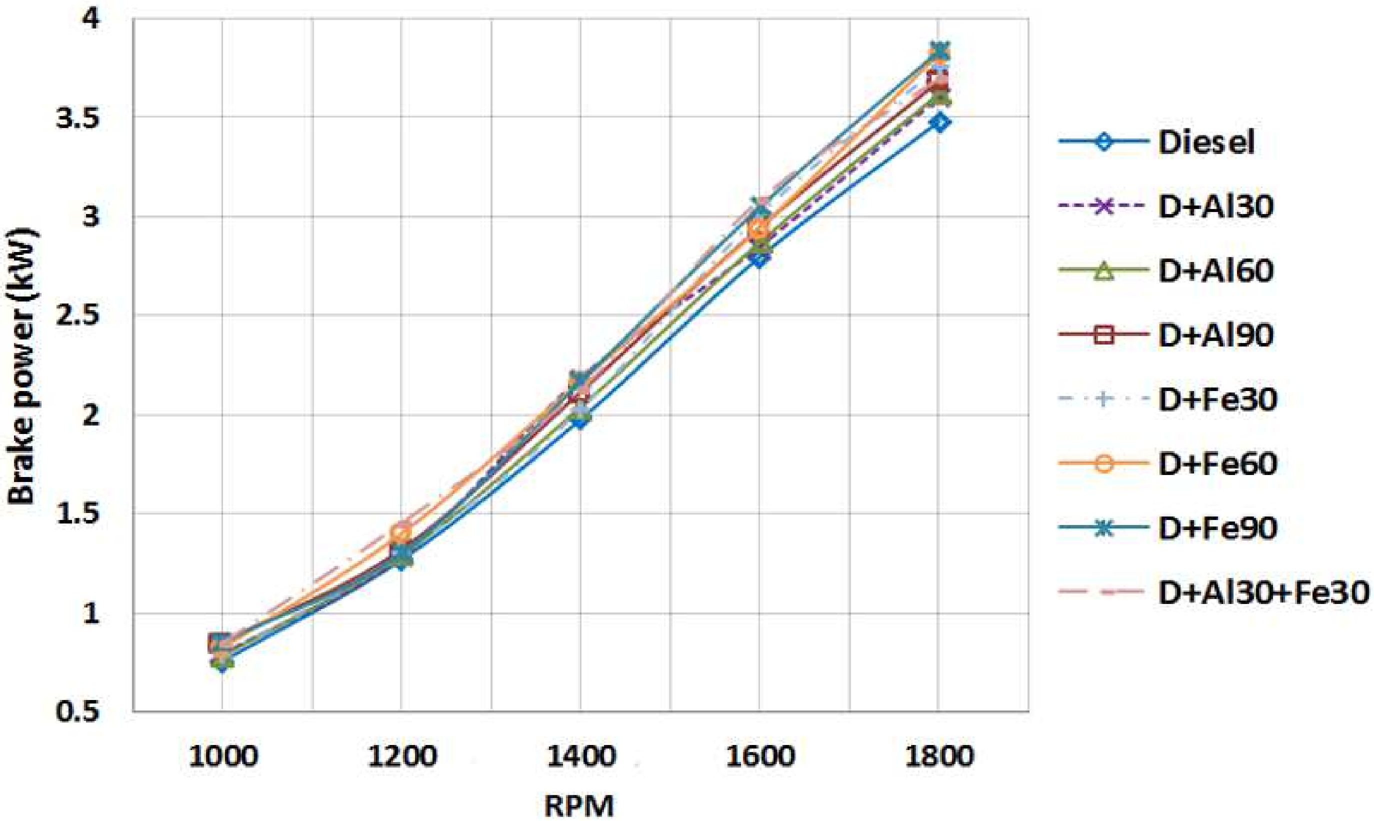



Figure 11

Brake power values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

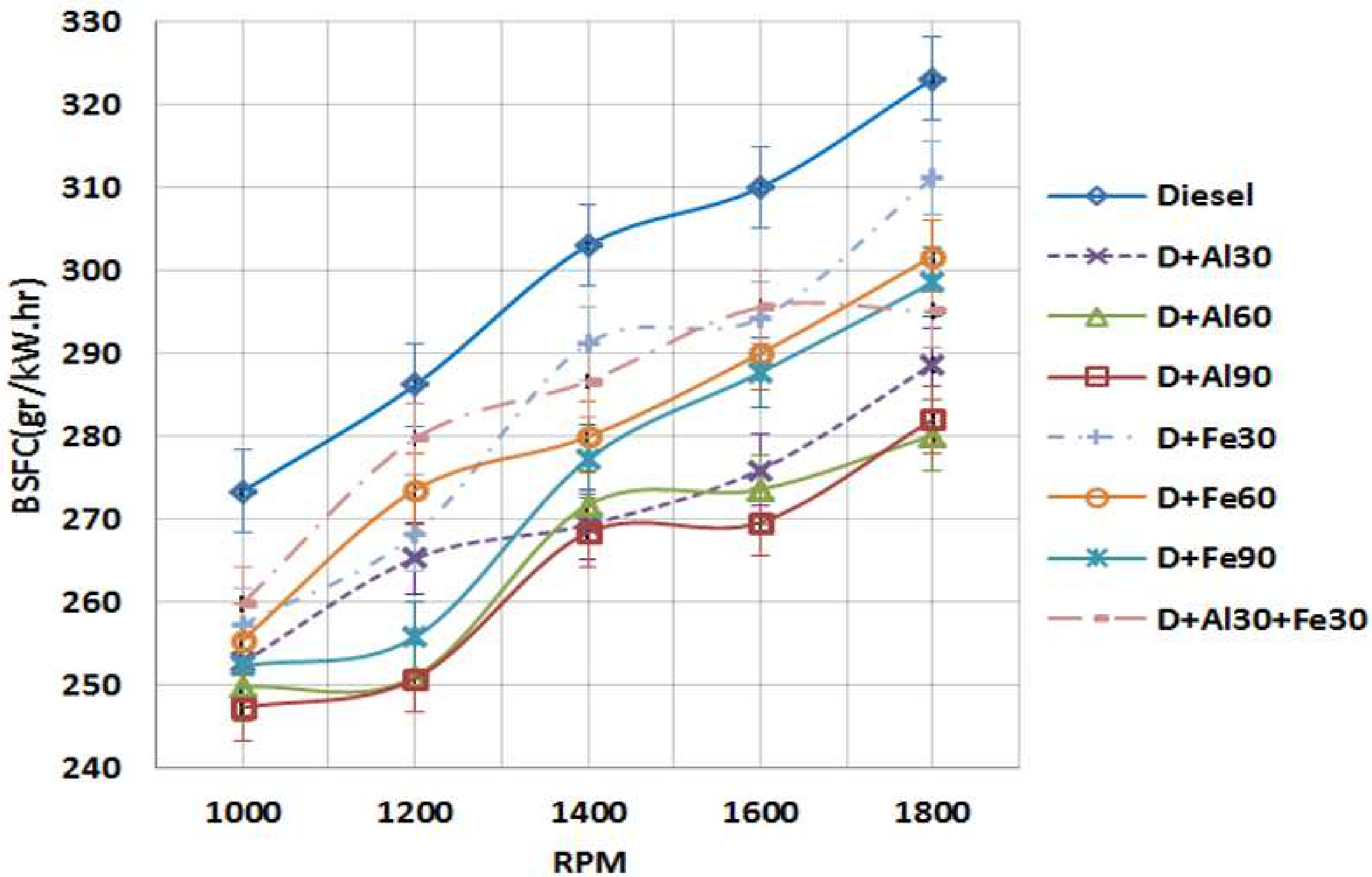
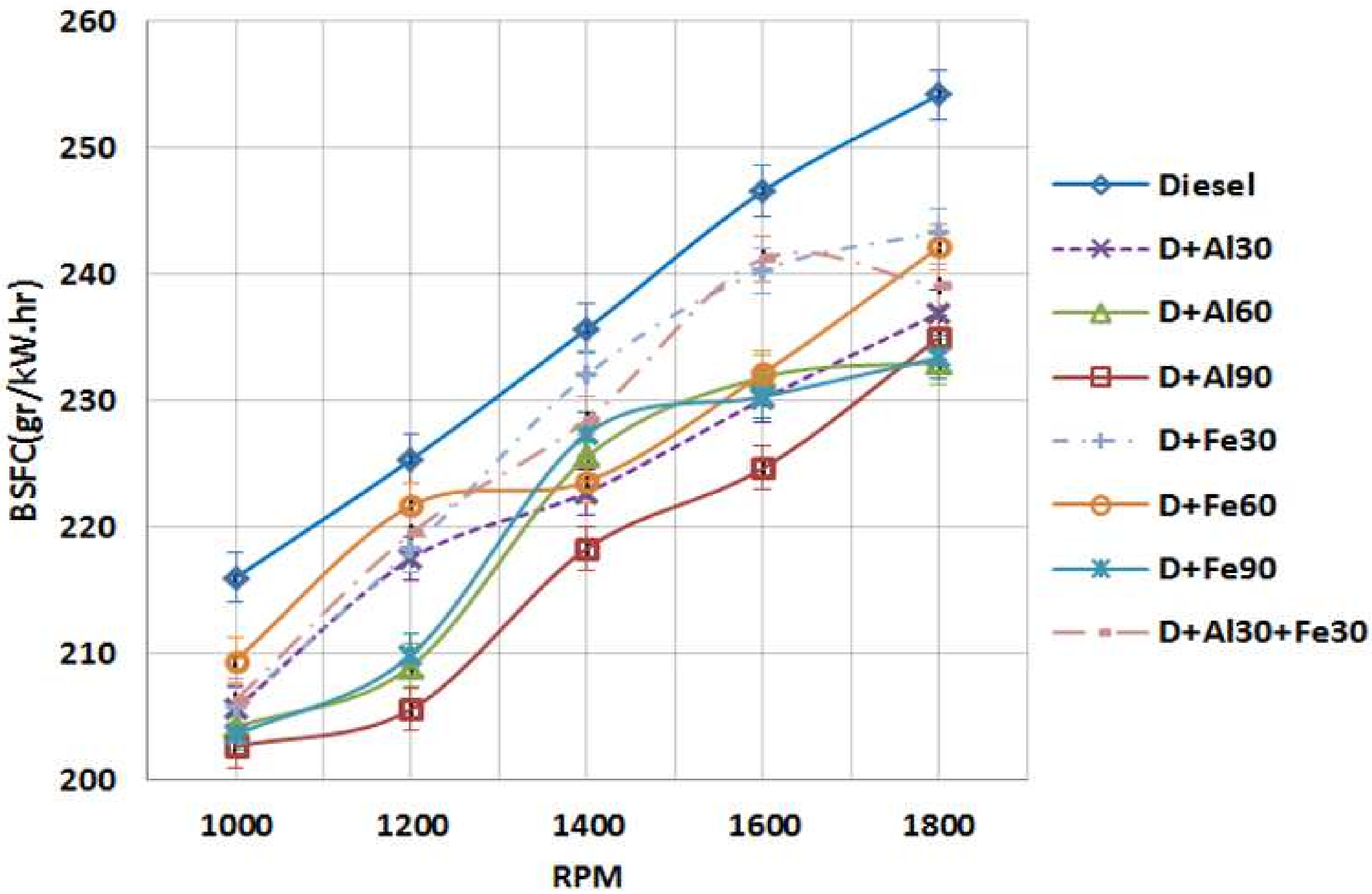



Figure 12

BSFC values versus rotational speed for various fuel blends at 50% engine load




## Figure 13

BSFC values versus rotational speed for various fuel blends at full engine load

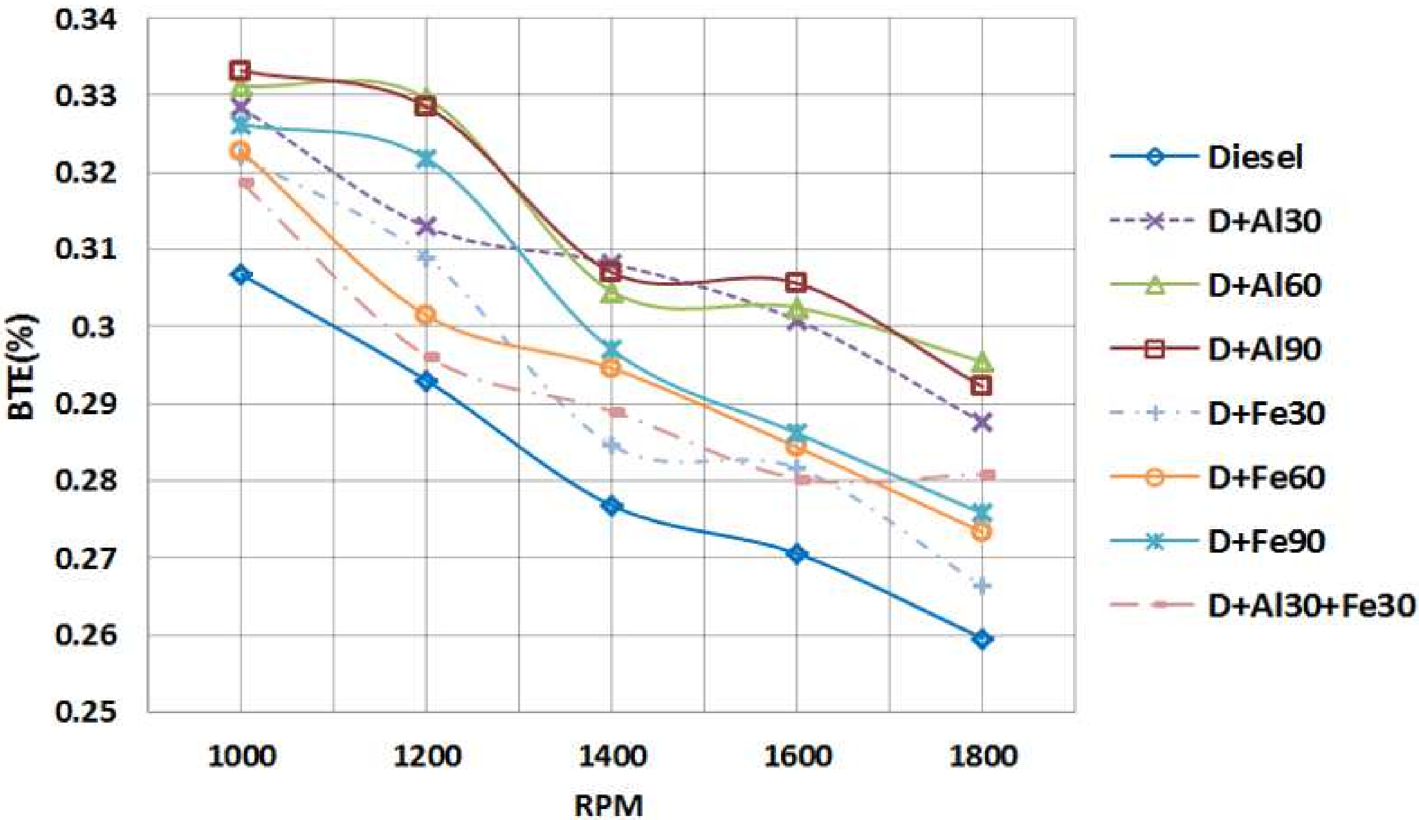



Figure 14

BTE values versus rotational speed for different nanoparticle-diesel fuel blends at 50% engine load

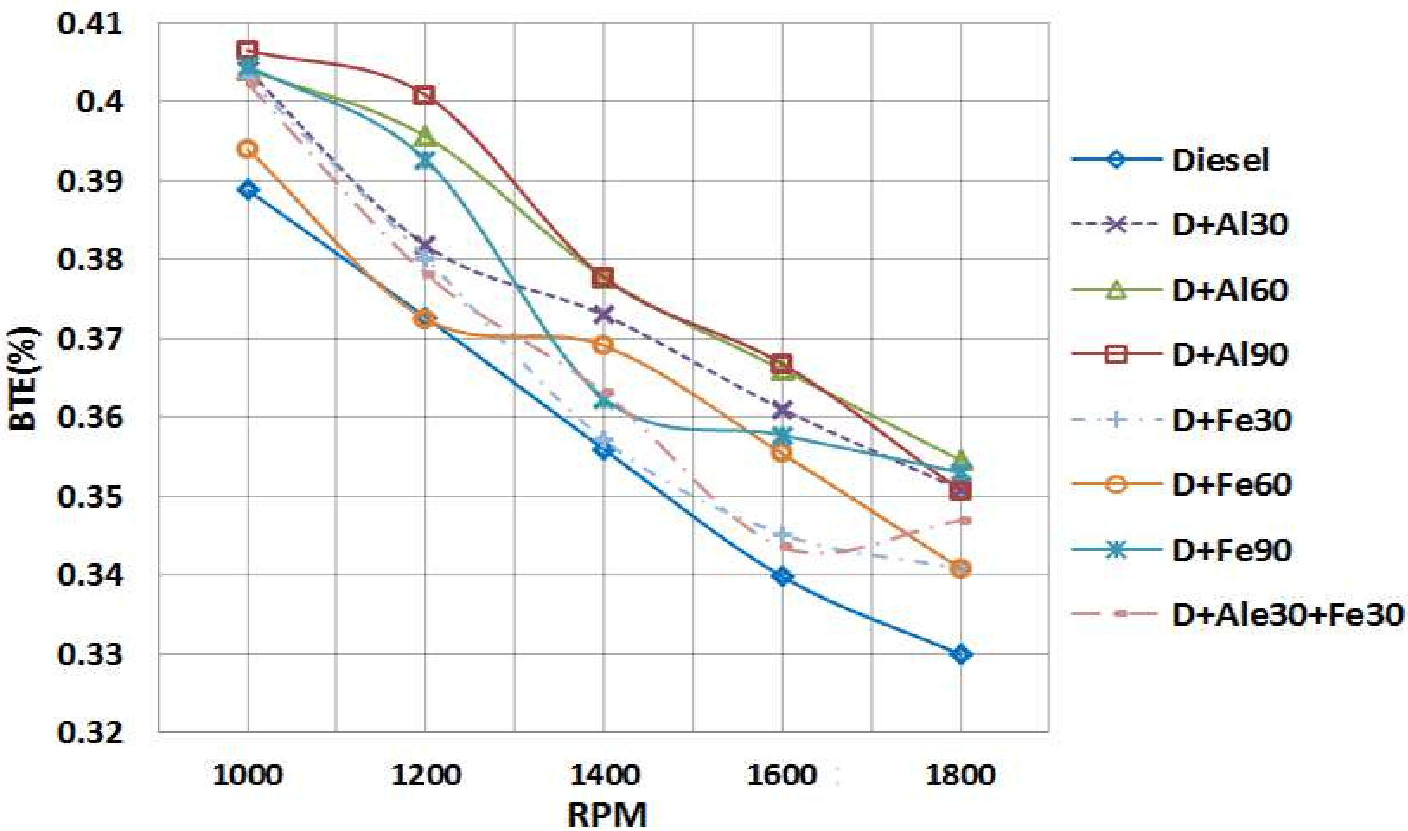


Figure 15

BTE values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

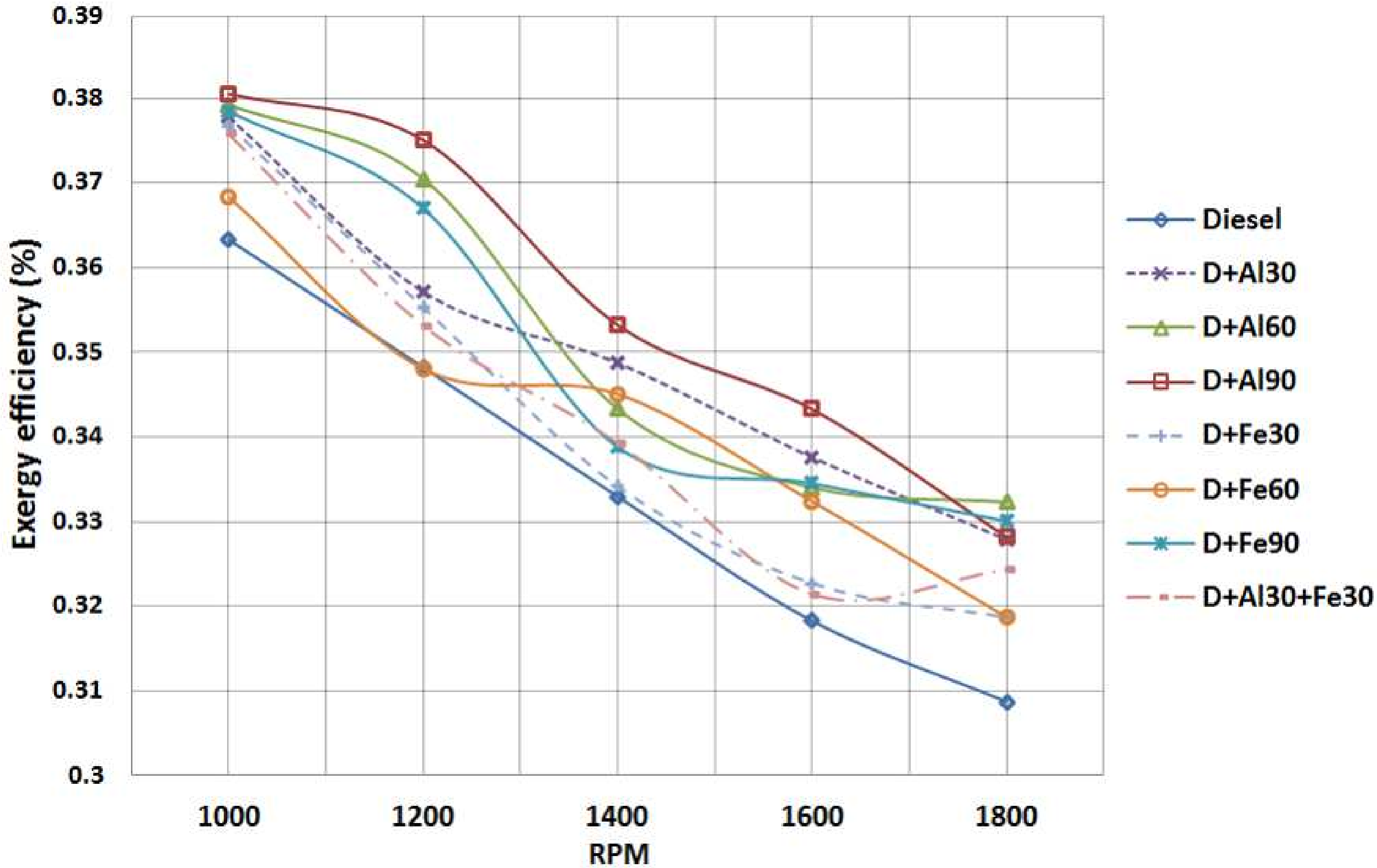



Figure 16

Exergy efficiency values versus rotational speed for different nanoparticle-diesel fuel blends at full engine load

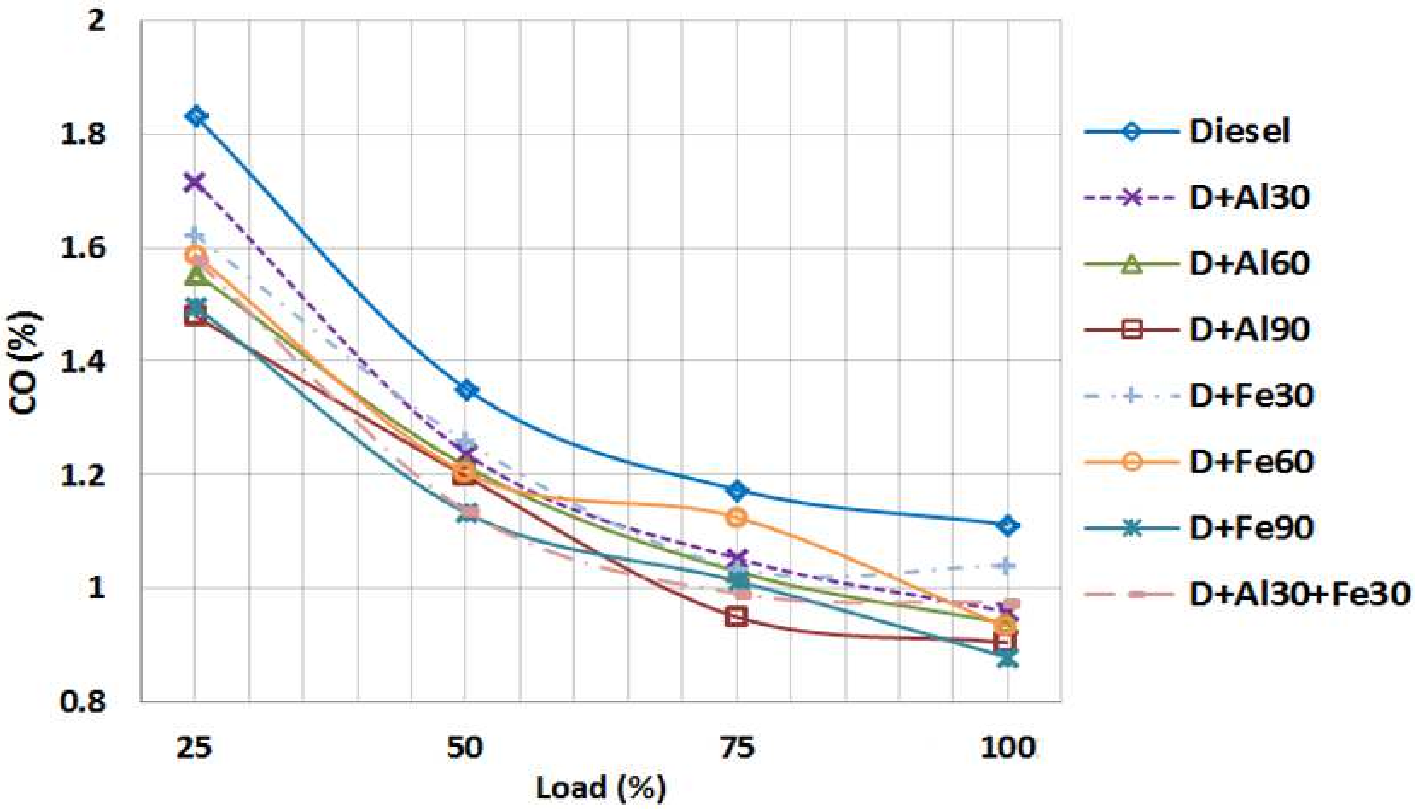



Figure 17

Variations of the CO emission against engine load for different nanoparticle-diesel fuel blends

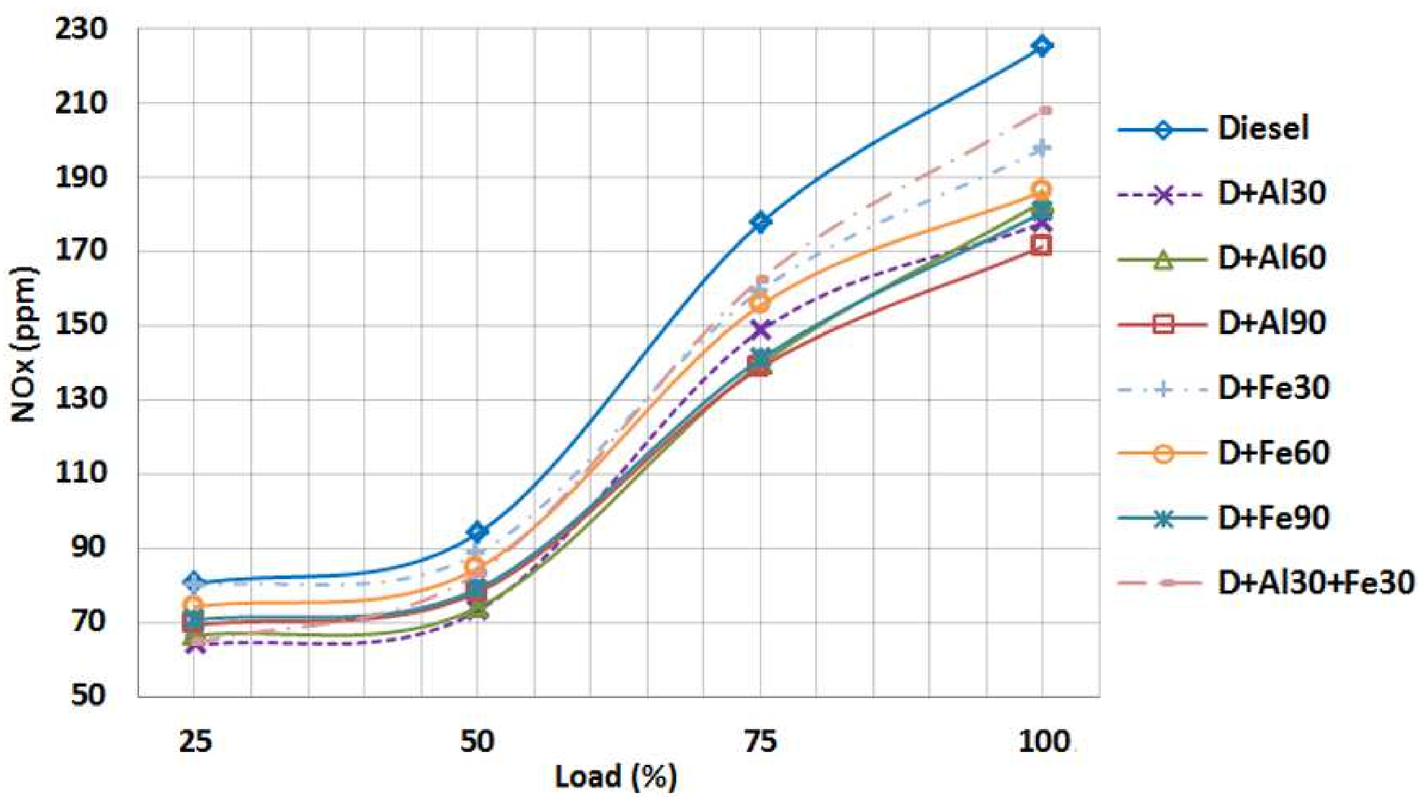


Figure 18

Variations of the NOx emission versus engine load for different nanoparticle-diesel fuel blends

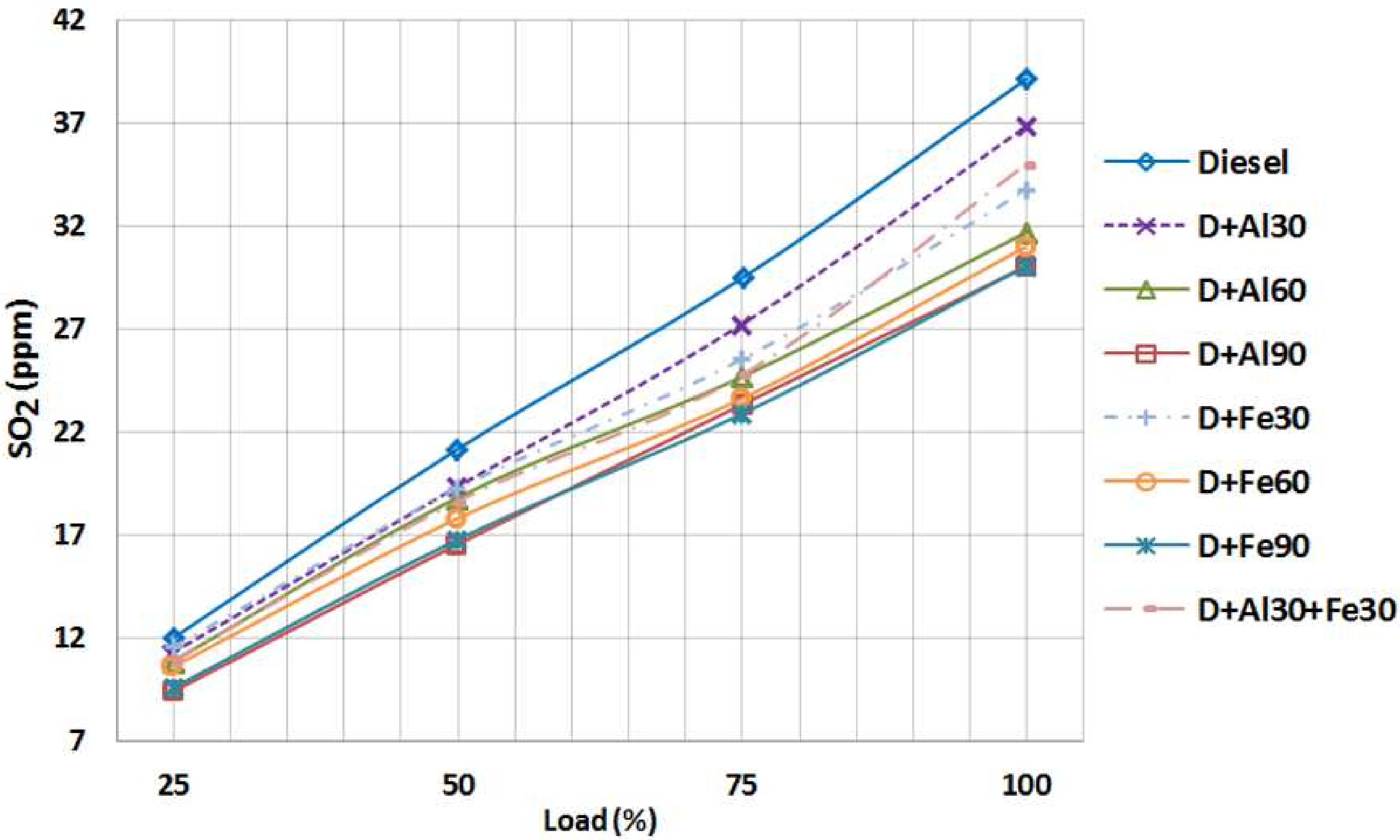



Figure 19

Variations of the SO2 emission against engine load for different nanoparticle-diesel fuel blends

## Supplementary Files

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- Slide1.tif
- Appendix1.docx