ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Tayfun ÖZGÜR

INVESTIGATION OF NANOPARTICLE ADDITIVES TO THE BIODIESEL AND DIESEL FUELS FOR IMPROVEMENT OF THE PERFORMANCE AND EXHAUST EMISSIONS IN A COMPRESSION IGNITION ENGINE

DEPARTMENT OF MECHANICAL ENGINEERING

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ABSTRACT

MSc THESIS

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Worldwide energy demand has been growing steadily during the past five decades, and most experts believe that this trend will continue to rise. The amount of emitted harmful emission gases increases in parallel with increasing energy consumption. This increase has forced many countries to take various precautions and various restrictions on emitted emissions have been carried. In this study effects of addition of oxygen containing nanoparticle additives to diesel and biodiesel fuels on diesel and biodiesel fuel properties and at the same time effects on diesel engine performance and emissions were investigated. Nine different nanoparticle additives namely MgO, Al_2O_3, TiO_2, ZnO, SiO_2, Fe_2O_3, NiO, $NiFe_2O_4$ and $Zn_{0.5}Ni_{0.5}Fe_2O_4$ were added to diesel fuel at the addition dosage of 25, 50 and 100 ppm and three of them namely MgO, SiO_2 and NiO were added to biodiesel fuel at the addition dosage of 25 and 50 ppm. Fuel properties, engine performance and emission characteristics of obtained modified fuels were examined. As a result of this study optimum additive and addition dosage was determined and engine emission values namely NO_x and CO were decreased with the addition of nanoparticles.

Key Words: Nanoparticle, Fuel Additives, Fuel Properties, Engine performance, Exhaust emissions

ÖZ

YÜKSEK LİSANS TEZİ

DİZEL MOTORLARDA PERFORMANS VE EGZOZ EMİSYONLARININ İYİLEŞTİRİLMESİ İÇİN BİYODİZEL VE DİZEL YAKITLARINA İLAVE EDİLEN NANOPARTİKÜL KATKILARININ İNCELENMESİ

Tayfun ÖZGÜR

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Dünyadaki enerji talebi son 50 yıldır artış göstermekte olup birçok uzman tarafından bu artışın önümüzdeki yıllarda da devam edeceği tahmin edilmektedir. Artan enerji tüketimine paralel olarak salınan zararlı emisyon gazları miktarı da artmaktadır. Bu artış birçok ülkeyi çeşitli önlemler almaya zorlamış olup yayılan emisyonlara çeşitli sınırlamalar getirilmiştir. Bu çalışmada oksijen içerikli nanopartiküllerin dizel ve biyodizel yakıtlarına katkı olarak kullanılmasının dizel ve biyodizel yakıt özelliklerine etkisi ve aynı zamanda dizel motorların performans ve emisyonlarına etkileri incelenmiştir. MgO, Al_2O_3, TiO_2, ZnO, SiO_2, Fe_2O_3, NiO, $NiFe_2O_4$ ve $Zn_{0.5}Ni_{0.5}Fe_2O_4$ gibi 9 farklı nanopartikül 25 ppm, 50 ppm ve 100 ppm olarak dizel yakıtına MgO, SiO_2 ve NiO gibi üç nanopartikül de 25 ve 50 ppm olarak biyodizel yakıtına ilave edilmiştir. Elde edilen karışımların yakıt özellikleri ve motor performans ve emisyon karakteristikleri incelenmiştir. Yapılan çalışma sonucunda en uygun olan katkı maddesi ve katkı dozajı belirlenmiş ve kullanılan nanopartikül katkılarının NO_x ve CO gibi motor emisyon değerlerini azaltığı gözlemlenmiştir.

Anahtar Kelimeler: Nanopartikül, Yakıt katkı maddesi, Yakıt özellikleri, Motor performansı, Egzoz emisyonları

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LIST OF ABBREVIATIONS AND NOMENCLATURE

NO_x	: Nitrogen Oxide
CO	: Carbon Monoxide
CO	: Carbon Dioxide
NaOH	: Sodium Hydroxide
CH_3OH	: Methanol
RME	: Rapeseed Methyl Ester
ppm	: Particle Per Million
PP	: Pour Point
EN 590	: European petrodiesel standard
EN 14214	: European Biodiesel Standard
Al_2O_3	: Aluminum Oxide
MgO	: Magnesium Oxide
TiO_2	: Titanium Oxide
ZnO	: Zinc Oxide
SiO_2	: Silicon Oxide
Fe_2O_3	: Iron Oxide
NiO	: Nickel Oxide
$NiFe_2O_4$	: Nickel Iron Oxide
$Zn_{0.5}Ni_{0.5}Fe_2O_4$	: Nickel Zinc Iron Oxide
g	: Gram
L	: Liter
nm	: Nanometer

1. INTRODUCTION

Worldwide energy demand has been growing steadily during the past five decades, and most experts believe that this trend will continue to rise. The vast majority of the world's primary energy demand is presently being met by fossil fuels, such as oil, natural gas and coal. According to BP's Statistical Review of World Energy 2009, the world's primary energy consumption in 2007 was 11,104 million tons of oil equivalents (Mtoe), of which 88% was provided by fossil fuels. World primary energy demand has risen nearly 40% since 1990, and it is expected to rise more than by 50% between now and 2030. In 2030, it is will reach 17,010 Mtoe and fossil fuels will continue to dominate the world energy mix, accounting for 80% of the world energy demand, according to projections of the International Energy Agency's (IEA) World Energy Outlook 2008 (WEO-2008) reference scenario (Erdem, 2010).

As shown in Fig. 1, in 2008 world primary energy use rose by 1.4%, with the increase rate dropping, due to rising prices, the recent economic downturn, and increases in energy efficiency, but is likely to rise again soon with the economy, as the large developing countries in Asia keep improving their standard of living, China's rose by 7.2% (lowest since 2002), India's by 5.6%, and some significant drops are those of the EU -0.56%, Japan -1.9%, US -2.8%, and led by Australia -4.2% (Lior, 2010).

Today, most of the energy used comes from fossil fuels: petroleum, coal, and natural gas. While fossil fuels are still being created today by underground heat and pressure, they are being consumed more rapidly than they are being created. For that reason, fossil fuels are considered non-renewable; that is, they are not replaced as soon as we use them. The renewable energy sources such as biomass, hydro, wind, solar (thermal and photovoltaic), geothermal, marine, and hydrogen will play an important role in the future. By 2040 approximately half of the global energy supply will come from renewables, and electricity generation from renewables will be more than 80% of the total global electricity supply (Demirbaş, 2008).

According to the International Energy Agency (IEA), scenarios developed for the USA and the EU indicate that near-term targets of up to 6% displacement of petroleum fuels with renewable biofuels appear feasible using conventional biofuels, given available cropland. A 5% displacement of gasoline in the EU requires about 5% of the available cropland to produce ethanol while in the USA 8% is required. A 5% displacement of diesel requires 13% of cropland in the USA, and 15% in the EU (Demirbaş, 2009).

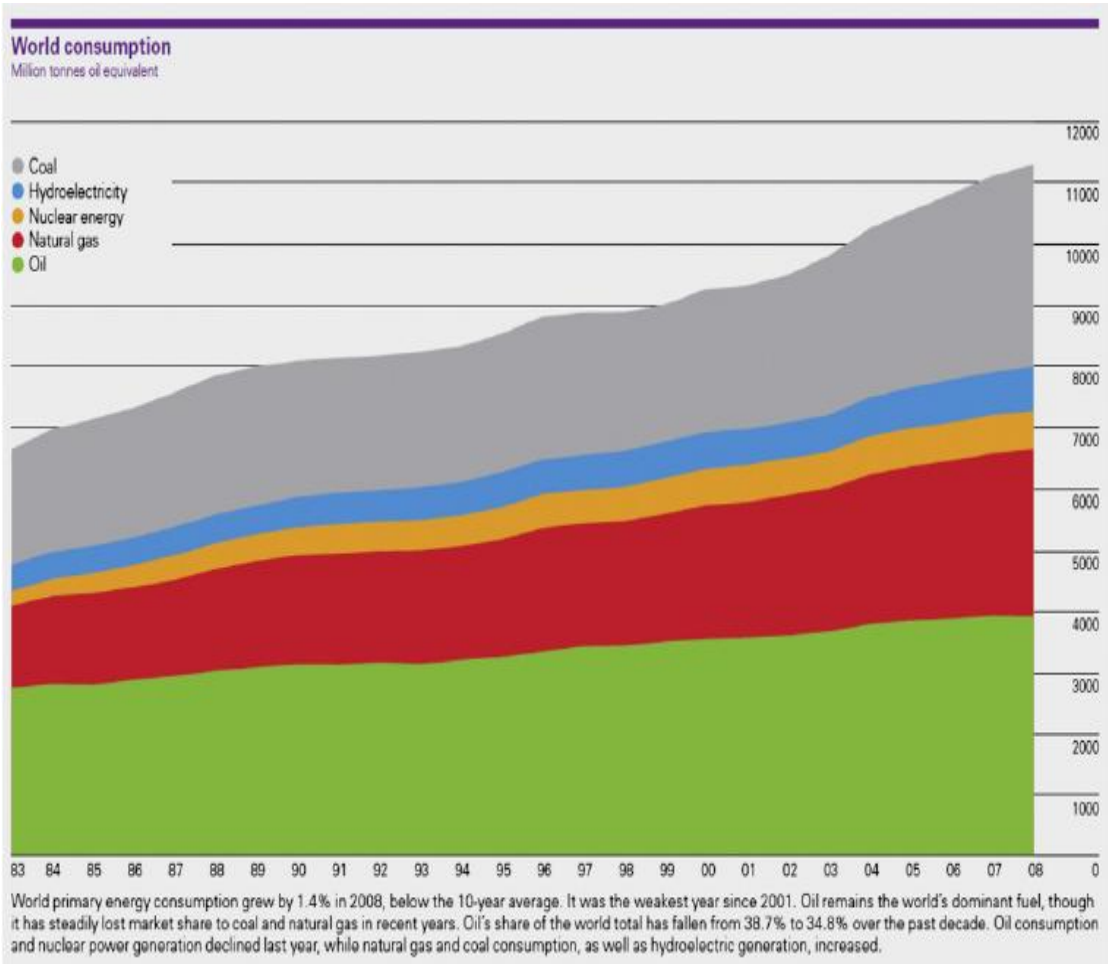


Figure 1.1. World primary energy consumption 1983-2008 (BP Statistical Review World Energy, 2009)

The energy sources must be evaluated by considering some factors such as remaining reserves, geographical distribution, production shares, stability of pricing, commercial status, source reliability and environmental effects. In the viewpoint of all these factors, renewable energy technologies are standing out in the future energy

generation. As the renewables rapidly become more and more important regarding to native resources and greenhouse gas emissions, the urge for Turkey to implement those increases accordingly (Özgür, 2008).

Although Turkey has almost all kinds of energy resources, it is an energy importing country; more than half of the energy requirement has been supplied by imports. Therefore, it seems that if the country wants to supply its demand by domestic and clean energy resources, the transition to renewable energy resources must be realized in a reasonable time period. When it is examined energy consumption data of Turkey, it is realized that oil has the biggest share in total primary energy consumption. The high level of dependence on imported petroleum and natural gas is the dominant factor in Turkey's pattern of energy consumption. While the share of petroleum in consumption of commercial primary energy increase 3.5% from 2003 to 2004, the share of natural gas in consumption of commercial primary energy grow 5% from 2003 to 2004 (Akpınar et al., 2007).

Table 1.1. Turkey's primary energy production and consumption (Mtoe)

Energy source	Production		Consumption		Increase (2003–2004) in consumption
	2003-year	2004-year	2003-year	2004-year	Percentage
Fossil fuels	13.782	13.566	72.072	75.434	+4.7
Oil	2.494	2.390	31.806	32.922	+3.5
Natural gas	0.511	0.644	19.450	20.426	+5.0
Coal	10.777	10.532	20.816	22.086	+6.1
Nuclear	–	–	–	–	–
Renewables	10.001	10.766	10.001	10.766	+7.7
Hydro	3.038	3.963	3.038	3.963	+30.4
Geothermal	0.860	0.891	0.860	0.891	+3.6
Solar	0.350	0.375	0.350	0.375	+7.1
Wind	0.005	0.005	0.005	0.005	0
Comb. renew. and wastes	5.748	5.532	5.748	5.532	−3.9
Total	23.783	24.332	82.073	86.200	+5.0

Turkey's primary energy sources include hydropower, geothermal, lignite, hard coal, oil, natural gas, wood, animal and plant wastes, solar and wind energy. In 2004, primary energy production and consumption has reached 24.332 million tonnes (Mt) of oil equivalent (Mtoe) and 86.20 Mtoe, respectively. Table 1 shows the Turkey's primary energy consumption and production in 2003 and 2004. Fossil fuels provided about 87.5% of the total energy consumption of the year 2004, with oil (38.2%) in first place, followed by coal (25.6%) and natural gas (23.7%). Turkey has not utilized nuclear energy yet. The Turkish coal sector, which includes hard coal as well as lignite, accounts for nearly one half of the country's total primary energy production, with lignite being the main domestic energy source at 9.141 Mtoe in 2004. The renewables collectively provided 12.5% of the primary energy, mostly in the form of combustible renewables and wastes (6.4%), hydropower (about 4.6%), geothermal (1.0%), and much less by other renewable energy resources (approximately 0.5%) (Akpınar et al., 2007).

Known petroleum reserves are limited resources and are estimated to be depleted in less than 50 years at the present rate of consumption. The dramatic increase in the price of petroleum, the finite nature of fossil fuels, increasing concerns regarding environmental impact, especially related to greenhouse gas emissions, and health and safety considerations are forcing the search for new energy sources and alternative ways to power the world's motor vehicles. Interest in the use of bio-fuels worldwide has grown strongly in recent years due to the high oil prices, concerns about climate change from greenhouse gas emissions and the desire to promote domestic rural economies. The bio-fuel industry's potential as a source of income and large new markets for rural and small farmers is of great interest. The growing international demand for bio-fuel is of particular interest to developing countries seeking opportunities for economic growth and trade. Developing countries have a comparative advantage for bio-fuel production because of greater availability of land, favorable climatic conditions for agriculture and lower labor costs. However, there may be other socioeconomic and environmental implications affecting the potential for developing countries to benefit from the increased global demand for

bio-fuel. Large-scale production of bio-fuels offers an opportunity for certain developing countries to reduce their dependence on oil imports. In developed countries there is a growing trend towards employing modern technologies and efficient bioenergy conversion using a range of bio-fuels, which are becoming cost-wise competitive with fossil fuels. For that reason, alternate transportation fuels such as bioethanol, biodiesel, and bio-hydrogen will play an important role in the world's future (Balat and Balat, 2009).

The increasing industrialization and motorization of the world has led to a steep rise for the demand of petroleum products. Petroleum based fuels are obtained from limited reserves. These finite reserves are highly concentrated in certain regions of the world. Therefore, those countries not having these resources are facing a foreign exchange crisis, mainly due to the import of crude oil. Hence, it is necessary to look for alternative fuels, which can be produced from materials available within the country. In addition, the use of vegetable oil as fuel is less polluting than petroleum fuels (Ramadhas et al., 2004).

Methyl esters of vegetable oils (biodiesels) have several outstanding advantages among other new-renewable and clean-engine fuel alternatives. Methanol as a monoalcohol is generally used in the transesterification reaction of triglycerides in the presence of alkali as a catalyst. Methanol is a relatively inexpensive alcohol. Several common vegetable oils such as sunflower, palm, rapeseed, soybean, cottonseed, and corn oils and their fatty acids can be used as the sample vegetable oil. Biodiesel is easier to produce and cleaner with equivalent amounts of processing when starting with clean vegetable oil. Tallow, lard, and yellow grease biodiesels require additional processing at the end of the transesterification process due to the presence of high free fatty acids. Diesel derived from rapeseed oil is the most common biodiesel available in Europe, while soybean biodiesel predominates in the United States (Demirbaş, 2008).

Biodiesel is a clear amber-yellow liquid with a viscosity similar to that of petrodiesel. Biodiesel is non-flammable and, in contrast to petrodiesel, is non-explosive, with a flash point of 150 ^{o}C for biodiesel as compared to 60^{o}C for petrodiesel. Unlike petrodiesel, biodiesel is biodegradable and non-toxic, and it

significantly reduces toxic and other emissions when burned as a fuel. Currently, biodiesel is more expensive to produce than petrodiesel, which appears to be the primary factor in preventing its more widespread use. Current worldwide production of vegetable oil and animal fat is not enough to replace liquid fossil fuel use (maximum replacement percentage: *ca.* 20 to 25%) (Bala, 2005).

Biodiesel is briefly defined as the monoalkyl esters of vegetable oils or animal fats. Biodiesel is the best candidate for diesel fuels in diesel engines. Biodiesel burns like petroleum diesel as it involves regulated pollutants. On the other hand biodiesel probably has better efficiency than gasoline. Biodiesel also exhibits great potential for compression-ignition engines. Diesel fuel can also be replaced by biodiesel made from vegetable oils. Biodiesel is now mainly being produced from soybean, rapeseed, and palm oils. The higher heating values (HHVs) of biodiesels are relatively high. The HHVs of biodiesels (39 to 41 MJ/kg) are slightly lower than those of gasoline (46 MJ/kg), petrodiesel (43 MJ/kg), or petroleum (42 MJ/kg), but higher than coal (32 to 37 MJ/kg) (Demirbaş, 2008).

Biodiesel is an alternative fuel for diesel engines that is receiving great attention world wide. Although it attracts the most attention because it is renewable, it can be used either pure or in blends with diesel fuel in unmodified diesel engines, and it reduces some exhaust pollutants. It is also attractive because it can be produced easily from common feedstocks. However, the relative simplicity of biodiesel production can disguise the importance of maintaining high quality standards for any fuel supplied to a modern diesel engine. It is essential to the growth of the biodiesel industry that all fuel produced and sold meet these quality standards (Gerpen et al., 2004).

Due to the increase in the price of the petroleum and the environmental concerns about pollution coming from the car gases, biodiesel is becoming a developing area of high concern. There are different ways of production, with different kinds of raw materials: refine crude or frying oils. Also there are different types of catalyst, basic ones such as sodium or potassium hydroxides, acids such as sulfuric acid, ion exchange resins, lipases and supercritical fluids (Marchetti et al., 2007).

The advantages of biodiesel as diesel fuel are its portability, ready availability, renewability, higher combustion efficiency, and lower sulfur and aromatic content, higher cetane number, and higher biodegradability. The main advantages of biodiesel given in the literature include its domestic origin, which would help reduce a country's dependency on imported petroleum, its biodegradability, high flash point, and inherent lubricity in the neat form (Demirbaş, 2008).

The major disadvantages of biodiesel are its higher viscosity, lower energy content, higher cloud point and pour point, higher nitrogen oxide (NOx) emissions, lower engine speed and power, injector coking, engine compatibility, high price, and greater engine wear. The technical disadvantages of biodiesel/fossil diesel blends include problems with fuel freezing in cold weather, reduced energy density, and degradation of fuel under storage for prolonged periods. One additional problem is encountered when blends are first introduced into equipment that has a long history of pure hydrocarbon usage. Hydrocarbon fuels typically form a layer of deposits on the inside of tanks, hoses, etc. Biodiesel blends loosen these deposits, causing them to block fuel filters. However, this is a minor problem, easily remedied by proper filter maintenance during the period following introduction of the biodiesel blend (Wardle, 2003).

Biodiesel, commercial diesel fuel, and their blends were used as the fuel of a direct injection (DI) compression ignition engine. Criteria pollutant emissions from biodiesel blends are now becoming a relevant subject due to the increase in consumption of this renewable fuel worldwide. Biodiesel is the first and only alternative fuel to commercial diesel to have a complete evaluation of emission results. The exhaust gas emissions are reduced with an increase in biodiesel concentration of the fuel blend. The emission forming gases such as carbon dioxide and carbon monoxide from combustion of biodiesel hydrocarbons are generally less than those of diesel fuel. The lower percentage of biodiesel blends emits very low amount of carbon dioxide (CO_2) in comparison with diesel. The engine emits more carbon monoxide (CO) using diesel as compared to that of biodiesel blends under all loading conditions. With increasing biodiesel percentage, CO emission level

decreases. Sulfur emissions are essentially eliminated with pure biodiesel. The torque values of commercial diesel fuel are greater than those of biodiesel. The brake power of biodiesel is nearly the same as with diesel fuel. The specific fuel consumption values of biodiesel are greater than those of commercial diesel fuel. The effective efficiency and effective pressure values of commercial diesel fuel are greater than those of biodiesel. Biodiesel methyl esters improve the lubrication properties of the diesel fuel blend. Biodiesel reduced long-term engine wear in diesel engines. Even biodiesel levels below 1% can provide up to a 30% increase in lubricity (Demirbaş, 2009).

One of the most common blends of biodiesel contains 20 volume percent biodiesel and 80 volume percent conventional diesel (B20). For soybean-based biodiesel at this concentration, the estimated emission impacts for percent change in emissions of NO_x, PM, HC, and CO were +20%, –10.1%, –21.1%, and –11.0%, respectively (EPA, 2002). The use of blends of biodiesel and diesel oil are preferred in engines in order to avoid some problems related to the decrease of power and torque, and to the increase of NO_x emissions (a contributing factor in the localized formation of smog and ozone) that occurs with an increase in the content of pure biodiesel in a blend. Emissions of all pollutants except NO_x appear to decrease when biodiesel is used (Demirbaş 2009).

The global pollution of environment is generally caused by using of fossil-based fuels (petroleum, coal and natural gas). Many researches on the reduction of pollution have been in progress. For this purpose, some of the researches have been focused on fuel additives to reduce harmful emissions. Fuel properties are developed by using some additives to improve combustion efficiency and to decrease pollutant emissions. One of those additives is metallic based compounds, which have been used as combustion catalyst for hydrocarbon fuels (Keskin et al., 2010).

Although diesel engines are generally more efficient than spark ignition engines, emissions from the diesel engine are typically higher. This has resulted in a somewhat negative impact on its wide acceptance and use, especially in automotive applications. Recently, stringent emission legislation has been imposed worldwide on

the oxides of nitrogen (NO_x), and smoke and particulate matter emitted from automotive diesel engines (Sajith et al., 2010).

The aim of this thesis was to investigate effects of nanoparticle additives to the biodiesel and diesel fuels for improvement of the performance and exhaust emissions in a Compression Ignition Engine.

Furthermore the engine performance and exhaust emissions of diesel and biodiesel with nanoparticle additives were investigated experimentally in this study.

The Study presented in the thesis is separated into various sections. Section 2 discusses literature review. Section 3 presents the methods and materials used through out the experiments. Section 4 discusses the results from the study and Section 5 draws conclusions from the results.

2. PRELIMENARY WORK

Sajith et al. (2010), informed that experimental investigations on the influence of the addition of cerium oxide in the nanoparticle form on the major physicochemical properties and the performance of biodiesel were conducted. The physicochemical properties of the base fuel and the modified fuel formed by dispersing the catalyst nanoparticles by ultrasonic agitation are measured using ASTM standard test methods. The effects of the additive nanoparticles on the individual fuel properties, the engine performance, and emissions are studied, and the dosing level of the additive is optimized. Comparisons of the performance of the fuel with and without the additive are also presented. The cold temperature properties of biodiesel do not show significant variation, due to the addition of cerium oxide nanoparticles. Engine tests with the modified biodiesel at different dosing levels (20–80 ppm) of the additive showed an improvement in the efficiency of the engine. The flash point and the viscosity of biodiesel were found to increase with the inclusion of the cerium oxide nanoparticles. The emission levels of hydrocarbon and NO_x are appreciably reduced with the addition of cerium oxide nanoparticles.

Keskin et al. (2010), stated that influences of the metallic-based additives on fuel consumption and exhaust emissions of diesel engine were investigated. The metallic-based additives were produced by synthesizing of resin acid (abietic acid) with MnO_2 or MgO. These additives were doped into diesel fuel at the rate of 8 µmol/l and 16 µmol/l for preparing test fuels. Both additives improved the properties of diesel fuel such as viscosity, flash point, cloud point and pour point. The fuels with and without additives were tested in a direct injection diesel engine at full load condition. Maximum reduction of specific fuel consumption was recorded as 4.16%. CO emission and smoke opacity decreased by 16.35% and by 29.82%, respectively. NO_x emission was measured higher and CO_2 emission was not changed considerably with the metallic-based additives.

Keskin et al. (2008), stated that influences of tall oil biodiesel with Mg and Mo based fuel additives on diesel engine performance and emission were investigated. Tall oil resinic acids were reacted with MgO and MoO_2

stoichiometrically for the production of metal-based fuel additives (combustion catalysts). The metal-based additives were added into tall oil biodiesel (B60) at the rate of 4 µmol/l, 8µmol/l and 12 µmol/l for preparing test fuels. In general, both of the metal-based additives improved flash point, pour point and viscosity of the biodiesel fuel, depending on the rate of additives. A single cylinder DI diesel engine was used in the tests. Engine performance values did not change significantly with biodiesel fuels, but exhaust emission profile was improved. CO emissions and smoke opacity decreased by 56.42% and by 30.43%, respectively. In general, low NO_x and CO_2 emissions were measured with the biodiesel fuels.

Guru et al. (2002), informed that organic compounds of Mn, Mg, Cu and Ca metals were synthesized, and their solutions were used as Diesel fuel additives. The additives that achieved the greatest decrease in freezing point of Diesel fuel, its optimum rate of dosage and other performance effects were tested. The results showed that the organic based manganese gave the greatest decrease in freezing point. This additive reduced the freezing point to 12.4 ^oC at the rate of dosage of 54.2 µmol Mn/l Diesel fuel. It was established that the cetane number of Diesel fuel without the additive was 46.22, whereas the cetane number was 48.24 for Diesel fuel with the optimum amount of dosage. It was observed that the organic based manganese drops the viscosity and flash point and improves the contents of the exhaust gases.

Icingur and Altiparmak (2003), noted that the effects of different fuel cetane numbers (CNs) and fuel injection pressures on a Diesel engine emission and on the performance were investigated. For this purpose, the fuels with 46, 51, 54.5 and 61.5 CN were tested in a four cycle, four cylinder DI Diesel engine. Measurements were conducted for each of the injection pressures 100, 150, 200 and 250 bar. Keeping 150 bar injection pressure and the other parameters constant, the changes of engine performance for the different CNs were also tested at full load condition. The results showed that NO_x, SO_2 and CO emissions are reduced about 15% and 5%, respectively, when the fuel CN is increased for the standard injection pressure, but the smoke value is increased dramatically when the injection pressure is reduced to 100 bar. In contrast with the lower pressure, NO_x is increased and smoke is

decreased when the injection pressure is increased to 250 bar. Increases in engine torque by 5% and power output by 4% were observed at the maximum torque speed of 2500 min^{-1} when the CN is increased from 46 to 54.5. However, when increasing CN above 54.5, no significant increases in engine performance were observed.

Keskin et al. (2007), studied that biodiesel fuel and fuel additives were produced from crude tall oil that is a by-product in the pulp manufacturing by craft or sulphate pulping process. Fatty acids and resinic acids were obtained from crude tall oil by distillation method. Tall oil methyl ester (biodiesel) was produced from fatty acids. Resinic acids were reacted with NiO and MnO_2 stoichiometrically for production of metallic fuel additives. Each metallic fuel additive was added at the rate of 8 µmol/l and 12 µmol/l to make mixtures of 60% tall oil methyl ester 40% diesel fuel (TE60) for preparing test fuels. Metallic fuel additives improved properties of biodiesel fuels, such as pour point and viscosity values. Biodiesel fuels were tested in an unmodified direct injection diesel engine at full load condition. Specific fuel consumption of biodiesel fuels increased by 6.00%, however, in comparison with TE60, it showed trend of decreasing with adding of additives. Exhaust emission profile of biodiesel fuels improved. CO emissions and smoke opacity decreased up to 64.28% and 30.91% respectively. Low NOx emission was also observed in general for the biodiesel fuels.

Sayin et al. (2010), stated that the effects of methanol–diesel (M5, M10) and ethanol–diesel (E5, E10) fuel blends on the performance and exhaust emissions were experimentally investigated. For this work, a single cylinder, four-stroke, direct injection, naturally aspirated diesel engine was used. The tests were performed by varying the engine speed between 1000 and 1800 rpm while keeping the engine torque at 30 Nm. The results showed that brake specific fuel consumption and emissions of nitrogen oxides increased while brake thermal efficiency, smoke opacity, emissions of carbon monoxide and total hydrocarbon decreased with methanol–diesel and ethanol–diesel fuel blends.

Ozsezen and Canakci (2011), informed that the performance, combustion and injection characteristics of a direct injection diesel engine have been investigated experimentally when it was fueled with canola oil methyl ester (COME) and waste

(frying) palm oil methyl ester (WPOME). In order to determine the performance and combustion characteristics, the experiments were conducted at constant engine speeds under the full load condition of the engine. The results indicated that when the test engine was fueled with WPOME or COME instead of petroleum based diesel fuel (PBDF), the brake power reduced by 4–5%, while the brake specific fuel consumption increased by 9–10%. On the other hand, methyl esters caused reductions in carbon monoxide (CO) by 59–67%, in unburned hydrocarbon (HC) by 17–26%, in carbon dioxide (CO_2) by 5–8%, and smoke opacity by 56–63%. However, both methyl esters produced more nitrogen oxides (NO_x) emissions by 11–22% compared with those of the PBDF over the speed range.

Nabi et al. (2006), stated that the combustion and exhaust emissions with neat diesel fuel and diesel-biodiesel blends have been investigated. In the investigation, firstly biodiesel from non-edible neem oil has been made by esterification. The experiment has been conducted with neat diesel fuel and diesel-biodiesel blends in a four stroke naturally aspirated (NA) direct injection (DI) diesel engine. Compared with conventional diesel fuel, diesel-biodiesel blends showed lower carbon monoxide (CO), and smoke emissions but higher oxides of nitrogen (NO_x) emission. However, compared with the diesel fuel, NO_x emission with diesel-biodiesel blends was slightly reduced when EGR was applied.

Tuccar et al. (2009), informed that 13 different fuel blends were prepared with 5% to 10% diisopropylether, 5% to 40% canola biodiesel and also 5% to 90% diesel in order to improve problem causing viscosity and cold flow properties. The fuel properties (such as viscosity, density, heat capacity, Cetane number, Cetane index, sulphur content) and engine performance values (such as torque, power) of these fuel blends were measured and compared with diesel and pure canola biodiesel. Test results showed that, the fuel properties and engine performance values were close to the standard limits for diesel fuel, the viscocity and cold flow properties of biodiesel were improved and these blends could be used directly in diesel engines.

Alptekin and Canakci (2009), noted that methyl esters were produced from five edible vegetable oils (sunflower, soybean, canola, corn and cottonseed) and blended with two different diesel fuels at 2%, 5%, 10%, 20%, 50% and 75% on a

volume basis to characterize the key fuel properties of the blends such as density, viscosity, pour point, distillation temperatures and flash point. The results showed that the fuel properties of the blends were very close to those of diesel fuels at low concentrations up to 20% of methyl esters.

Qi et al. (2010), stated that an experimental investigation was conducted to evaluate the effects of using methanol as additive to biodiesel–diesel blends on the engine performance, emissions and combustion characteristics of a direct injection diesel engine under variable operating conditions. BD50 (50% biodiesel and 50% diesel in vol.) was prepared as the baseline fuel. Methanol was added to BD50 as an additive by volume percent of 5% and 10% (denoted as BDM5 and BDM10). The results indicate that the combustion starts later for BDM5 and BDM10 than for BD50 at low engine load, but is almost identical at high engine load. At low engine load of 1500 r/min, BDM5 and BDM10 show the similar peak cylinder pressure and peak of pressure rise rate to BD50, and higher peak of heat release rate than that of BD50. At low engine load of 1800 r/min, the peak cylinder pressure and the peak of pressure rise rate of BDM5 and BDM10 are lower than those of BD50, and the peak of heat release rate is similar to that of BD50. The crank angles at which the peak values occur are later for BDM5 and BDM10 than for BD50. At high engine load, the peak cylinder pressure, the peak of pressure rise rate and peak of heat release rate of BDM5 and BDM10 are higher than those of BD50, and the crank angle of peak values for all tested fuels are almost same. The power and torque outputs of BDM5 and BDM10 are slightly lower than those of BD50. BDM5 and BDM10 show dramatic reduction of smoke emissions. CO emissions are slightly lower, and NOx and HC emissions are almost similar to those of BD50 at speed characteristic of full engine load.

Qi et al. (2010), objected that the biodiesel produced from soybean crude oil was prepared by a method of alkaline-catalyzed transesterification. The effects of biodiesel addition to diesel fuel on the performance, emissions and combustion characteristics of a naturally aspirated DI compression ignition engine were examined. Biodiesel has different properties from diesel fuel. A minor increase in brake specific fuel consumption (BSFC) and decrease in brake thermal efficiency

(BTE) for biodiesel and its blends were observed compared with diesel fuel. The significant improvement in reduction of carbon monoxide (CO) and smoke were found for biodiesel and its blends at high engine loads. Hydrocarbon (HC) had no evident variation for all tested fuels. Nitrogen oxides (NO_X) were slightly higher for biodiesel and its blends. Biodiesel and its blends exhibited similar combustion stages to diesel fuel. The use of transesterified soybean crude oil can be partially substituted for the diesel fuel at most operating conditions in terms of the performance parameters and emissions without any engine modification.

Randazzo et al. (2010), informed that the effects of diesel oil–soybean biodiesel blends on a passenger vehicle exhaust pollutant emissions were investigated. Blends of diesel oil and soybean biodiesel with concentrations of 3% (B3), 5% (B5), 10% (B10) and 20% (B20) were used as fuels. Additionally, the effects of anhydrous ethanol as an additive to B20 fuel blend with concentrations of 2% (B20E2) and 5% (B20E5) were also studied. The emissions tests were carried out following the New European Driving Cycle (NEDC). The results showed that increasing biodiesel concentration in the fuel blend increases carbon dioxide (CO_2) and oxides of nitrogen (NO_X) emissions, while carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) emissions are reduced. The addition of anhydrous ethanol to B20 fuel blend proved it can be a strategy to control exhaust NO_X and global warming effects through the reduction of CO_2 concentration. However, it may require fuel injection modifications, as it increases CO, HC and PM emissions.

Rakopoulos et al. (2010), noted that an experimental investigation is conducted to evaluate the effects of using blends of n-butanol (normal butanol) with conventional diesel fuel, with 8%, 16% and 24% (by volume) n-butanol, on the performance and exhaust emissions of a standard, fully instrumented, four-stroke, high-speed, direct injection (DI), Ricardo/Cussons ‘Hydra’ diesel engine. The tests are conducted using each of the above fuel blends or neat diesel fuel, with the engine working at a speed of 2000 rpm andat three different loads. In each test, fuel consumption, exhaust smokiness and exhaust regulated gas emissions such as nitrogen oxides, carbon monoxide and total unburned hydrocarbons are measured. The smoke density was significantly reduced with the use of the butanol–diesel fuel

blends with respect to those of the neat diesel fuel, with this reduction being higher the higher the percentage of butanol in the blend. The NO_X emissions were slightly reduced with the use of the butanol–diesel fuel blends with respect to those of the neat diesel fuel, with this reduction being higher the higher the percentage of butanol in the blend. The CO emissions were reduced with the use of the butanol–diesel fuel blends with respect to those of the neat diesel fuel, with this reduction being higher the higher the percentage of butanol in the blend. On the contrary, the unburned hydrocarbons (HC) emissions were increased with the use of the butanol–diesel fuel blends with respect to those of the neat diesel fuel, with this increase being higher the higher the percentage of butanol in the blend. Concerning the engine performance with the butanol–diesel fuel blends against the neat diesel fuel case, with increasing percentage of butanol in the blends, a little higher specific fuel consumption was observed with corresponding slight increase of brake thermal efficiency and little lower exhaust gas temperatures.

Sayin et al. (2010), informed that the effects of injection pressure and timing on the performance and emission characteristics of a DI diesel engine using methanol (5%, 10% and 15%) blended-diesel fuel were investigated. The tests were conducted on three different injection pressures (180, 200 and 220 bar) and timings (15^o, 20^o, and 25^o CA BTDC) at 20 Nm engine load and 2200 rpm. The results indicated that brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC), and nitrogen oxides (NO_X) emissions increased as brake thermal efficiency (BTE), smoke opacity, carbon monoxide (CO) and total unburned hydrocarbon (THC) decreased with increasing amount of methanol in the fuel mixture. The best results were achieved for BSFC, BSEC and BTE at the original injection pressure and timing. For the all test fuels, the increasing injection pressure and timing caused to decrease in the smoke opacity, CO, THC emissions while NOx emissions increase.

Buyukkaya et al. (2010), reported that experimental tests were investigated to evaluate the performance, emission and combustion of a diesel engine using neat rapeseed oil and its blends of 5%, 20% and 70%, and standard diesel fuel separately. The results indicate that the use of biodiesel produces lower smoke opacity (up to 60%), and higher brake specific fuel consumption (BSFC) (up to 11%) compared to

diesel fuel. The measured CO emissions of B5 and B100 fuels were found to be 9% and 32% lower than that of the diesel fuel, respectively. The BSFC of biodiesel at the maximum torque and rated power conditions were found to be 8.5% and 8% higher than that of the diesel fuel, respectively. From the combustion analysis, it was found that ignition delay was shorter for neat rapeseed oil and its blends tested compared to that of standard diesel. The combustion characteristics of rapeseed oil and its diesel blends closely followed those of standard diesel.

Lertsathapornsuk et al. (2008), reported that household microwave (800W) was modified as a biodiesel reactor for continuous transethylation of waste frying palm oil. The high free fatty acid oil was simultaneously neutralized and transesterified with sodium hydroxide. With the ethanol to oil molar ratio of 12:1, 3.0% NaOH (in ethanol) and 30s residence time, the continuous conversion of waste frying palm oil to ethyl ester was over 97%. The waste palm oil biodiesel was then tested in a 100 kW diesel generator as a neat fuel (B100) and 50% blend with diesel No. 2 fuel (B50). The engine performance and emission are recorded. At the engine loads varied from 0 kW to 75 kW (at 25 kW intervals) of the maximum electrical rating, the performance of the neat and B50 are slightly lower than diesel No. 2 fuel. Emissions of NOx, CO and HC from B100 and B50 are lower than those of diesel No. 2 fuel, except that at the 75 kW engine load, where the B100 emits higher levels of NO_x than the diesel No. 2 fuel.

Lapuerta et al. (2008), concluded that experimental results were obtained by testing two different alcohol-derived biodiesel fuels: methyl ester and ethyl ester, both obtained from waste cooking oil. These biodiesel fuels were tested pure and blended (30% and 70% biodiesel content, volume basis) with a diesel reference fuel, which was tested too, in a 2.2 l, common-rail injection diesel engine. The operation modes were selected to simulate the European Driving Cycle. Pure biodiesel fuels, compared to the reference fuel, resulted in a slight increase in fuel consumption, in very slight differences in NO_x emissions, and in sharp reductions in total hydrocarbon emissions, smoke opacity and particle emissions (both in mass and number), despite the increasing volatile organic fraction of the particulate matter. The type of alcohol used in the production process was found to have a significant

effect on the total hydrocarbon emissions and on the particulate matter composition. As the alcohol used was more volatile, both the hydrocarbon emissions and volatile organic fraction of the particulate matter were observed to increase.

Canakci (2007), presented that the combustion characteristics and emissions of two different petroleum diesel fuels (No. 1 and No. 2) and biodiesel from soybean oil were compared. The tests were performed at steady state conditions in a four-cylinder turbocharged DI diesel engine at full load at 1400-rpm engine speed. The experimental results compared with No. 2 diesel fuel showed that biodiesel provided significant reductions in PM, CO, and unburned HC, the NOx increased by 11.2%. Biodiesel had a 13.8% increase in brake-specific fuel consumption due to its lower heating value. However, using No. 1 diesel fuel gave better emission results, NOx and brake-specific fuel consumption reduced by 16.1% and 1.2%, respectively. The values of the principal combustion characteristics of the biodiesel were obtained between two petroleum diesel fuels. The results indicated that biodiesel may be blended with No. 1 diesel fuel to be used without any modification on the engine.

Utlu and Kocak (2008), stated that the effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions were studied. They used waste frying oil (WFO) methyl ester as an experimental material for their performance and emissions tests. They observed that the measures of torque, power; specific fuel consumptions are nearly the same. In addition, amount of emission such as CO, CO_2, NO_x, and smoke darkness of waste frying oils were less than diesel fuel.

Ozsezen et al. (2009), objected that the performance and combustion characteristics of a direct injection (DI) diesel engine fueled with biodiesels such as waste (frying) palm oil methyl ester (WPOME) and canola oil methyl ester (COME) were studied. In order to determine the performance and combustion characteristics, the experiments were conducted at the constant engine speed mode (1500 rpm) under the full load condition of the engine. The results indicated that when the test engine was fueled with WPOME or COME, the engine performance slightly weakened; the combustion characteristics slightly changed when compared to petroleum based diesel fuel (PBDF). The biodiesels caused reductions in carbon monoxide (CO),

unburned hydrocarbon (HC) emissions and smoke opacity, but they caused to increases in nitrogen oxides (NO_x) emissions.

3. MATERIAL AND METHOD

3.1. Biodiesel Production from Rapeseed Oil

In this study, the rapeseed oil was given by Sunar Mısır Corporation, a local oil factory at Cukurova Region. In order to produce biodiesel from rapeseed oil the biodiesel production equipments at the Çukurova University Mechanical Engineering Department Automotive Engineering Laboratories was used.

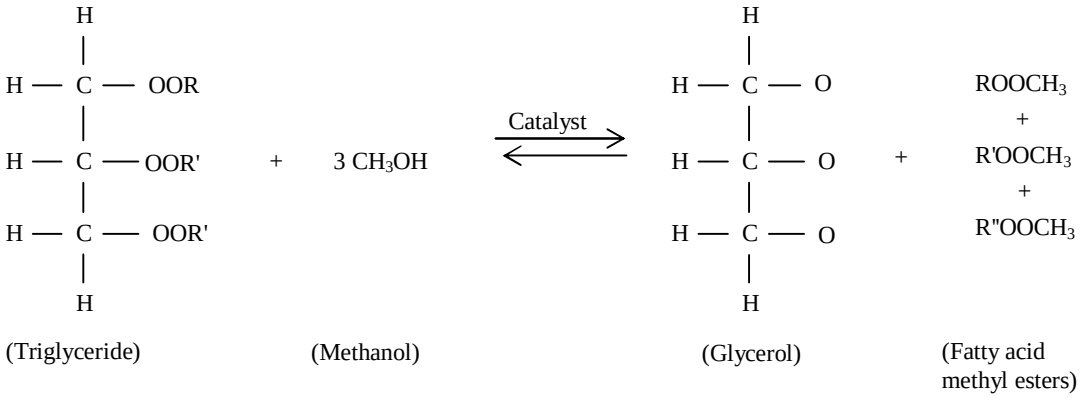


Figure 3.1. General equation for transesterification of triglycerides with methanol

Transesterification reaction (Figure 1) was carried out in a spherical glass reactor equipped with reflux condenser, stirrer and thermometer. Sodium hydroxide (NaOH) used as catalyst and methanol (CH_3OH) was chosen as alcohol. Methanol was preferred as alcohol because it is the cheapest alcohol. At the transesterification reaction, mol ratio of alcohol and oil was 6:1. 100% excess methanol was used to ensure that the reaction goes to completion. In order to obtain sodium methoxide, methanol and NaOH were mixed. Then sodium methoxide and rapeseed oil were mixed in the small scale reactor. Detailed view of small scale reactor can be seen in Figure 3.2. The mixture was heated up to 62-63 ^oC and kept at this temperature for one hour; during this period mixture was stirred continuously. At the end of the reaction period, the crude methyl ester was waited at separating funnel for 8 hours. And then, deep phase containing crude glycerin was separated from crude methyl esters. Then the crude methyl ester was washed three times with warm water. Water

and all the other substances precipitated at the bottom. After washing process crude methyl ester was dried at 105 ^{o}C for one hour. After the drying process, rapeseed methyl ester let to be cool down. In order to neglect the possibility of impurities the rapeseed methyl ester drained from paper filter. This production process was repeated for 2 times and each party collected in the same vessel to get a homogenous biodiesel. Flow diagram of biodiesel production process used in the study is shown in Figure 3.3.

4 g (0.4 wt %) of catalyst NaOH, dissolved in the required amount of methanol 200 g (20 wt %) was added to 1000 g of Rapeseed oil. Table 3.1 shows the chemicals used for production of biodiesel.

Table 3.1. Chemicals used for production of biodiesel

Materials	Units	Value
Rapeseed Oil	g	1000
Sodium hydroxide (NaOH)	g	4 (0.4 wt %)
Methanol (CH_3OH)	g	200 (20 wt %)
Reaction temperature	^{o}C	62-63

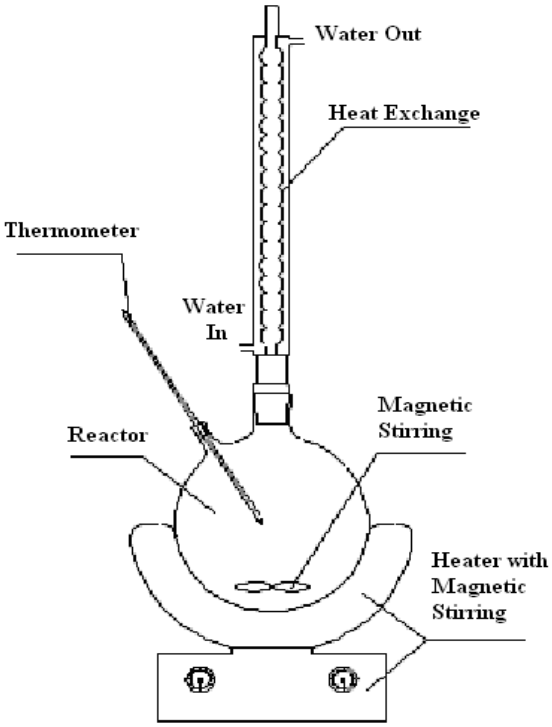


Figure 3.2. Small scale reactor

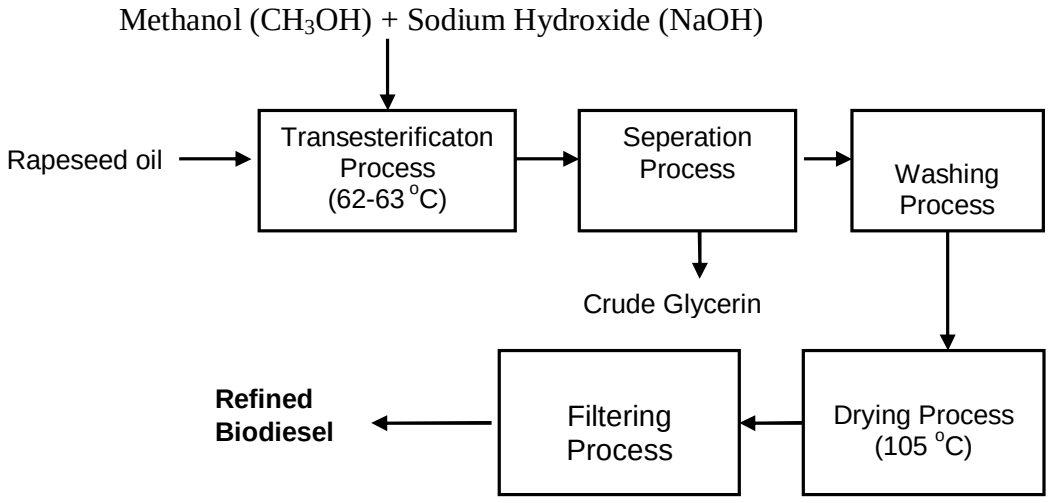


Figure 3.3. Flow diagram of biodiesel production from rapeseed oil

3.2. Preparation of Modified Fuels

The fuel used for the current investigation is a biodiesel product, derived from rapeseed oil and eurodiesel. The fuel additive used in this investigation is several nanoparticles given in the Table 3.2, in the form of commercially available nanoparticles of size 10 to 50 nanometers. The dosing level of the nanoparticle samples (by weight) in the base fuel was 25, 50 and 100 ppm. The required quantity of the nanoparticle sample required for each dosing level was measured using a precision electronic balance with sensitivity 0.0001 g and mixed with the fuel by means of an ultrasonic processor, applying a constant agitation time of one hour to produce a uniform suspension. The modified fuel was utilized immediately after preparation, in order to avoid any settling or for sedimentation to occur.

Table 3.2. Properties of nanoparticles used in the experiments

Nanoparticle	Symbol	Particle Size (nm)	Purity (%)	Cost (TL/g)
Aluminum Oxide	Al_2O_3	30	99.99	1.48
Magnesium Oxide	MgO	30	99.9	1.07
Titanium Oxide	TiO_2	10–50	99.99	1.69
Zinc Oxide	ZnO	50	99.9	1.16
Silicon Oxide	SiO_2	<30	99.99	1.48
Iron Oxide	Fe_2O_3	30	99.5	1.88
Nickel Oxide	NiO	30	99.9	1.27
Nickel Iron Oxide	$NiFe_2O_4$	30	99.9	2.11
Nickel Zinc Iron Oxide	$Zn_{0.5}Ni_{0.5}Fe_2O_4$	30	99.5	2.11

Sonic Vibra-Cell VC 750 (Figure 3.4) model ultrasonic processor was used to stir nanoparticles with diesel and biodiesel fuels homogeneously in order to obtain modified fuels. Nanoparticles were mixed with diesel and rapeseed methyl ester with pulsing time 10 seconds on 10 seconds off and 40% amplitude by means of ultrasonic processor. Technical Specifications of ultrasonic processor used in the experiments was given in Table 3.3.

Table 3.3. Techinical specifications of ultrasonic processor

POWER SUPPLY	Net power output:	750 Watts
	Frequency:	20 kHz
	Dimensions: (H x W x D):	235 x 190 x 340 mm
	Weight:	6.8 kg
SEALED CONVERTER	Part No:	Piezoelectric lead zirconate titanate crystals
	Diameter:	63.5 mm
	Length:	183 mm
	Weight:	900 g
	Cable length:	1.8 m
STANDART PROBE	Tip diameter:	13 mm with threaded end and replaceable tip or solid probe with non-replaceable tip
	Processing capability:	10 ml to 250 ml
	Length:	136 mm
	Weight:	340 g
	Material	Titanium alloy Ti-6Al-4



Figure 3.4. Sonic Vibra-Cell VC 750 model ultrasonic processor

3.3. Fuel Properties Measurement Methods

The fuel quality measurements of the blends were done according to EN 14214 and EN 590. The testing equipments and their measuring methods were briefly explained below.

3.2.1 Density Measurement:

The density measurement was done using Kyoto Electronics DA-130 type densimeter (Figure 3.5). This densimeter uses the resonant frequency method to measure the densities. With the densimeter we can also measure the specific weight, API gravity, % Brix, volume and mass alcohol rates. The measurement interval of the device is 0 to 2 g/cm^3 and 0 to 40 ºC. The device has a sensitivity of ±0.001 g/cm^3, and a stability of 0.0001 g/cm^3. The device is measuring according to the standards of TS 6311, ASTM D 4052-96.



Figure 3.5. Kyoto Electronics DA-130 portable densimeter

3.2.2 Viscosity Measurement:

To define kinematic viscosity it is useful to begin with the definition of viscosity. Simply stated, viscosity, which is also called dynamic viscosity (η), is the ease with which a fluid will flow. Technically it is the ratio of the shear stress to the shear rate for a fluid. In contrast, the kinematic viscosity (ν) is the resistance to flow of a fluid under gravity (Gerpen et al. 2004).

The viscosities of the fuels were measured with Saybolt Universal Viscosimeter (Figure 3.6) produced from Ubbelohde tube with ASTM D88 standards. The meaurement results were recorded in seconds. Then using a

conversion table the results were converted from SSU (saybolt universal second) to centistokes (cSt) unit. The measurements were done at 40 ºC according to the TS EN 14214 standard.



Figure 3.6. Saybolt Universal Viscosimeter

3.2.3 Cetane Number Measurement:

Perhaps the most important measure of ignition characteristics of diesel and/or biodiesel fuels is the cetane number, since it directly pertains to ignition within compression ignition engines. The cetane number is the primary specification measurement used to match fuels and engines. It is commonly used by refiners, marketers and engine manufacturers to describe diesel fuels (Gerpen et al. 2004).

The Cetane number and indexes were measured by Zeltex ZX440 (Figure 3.7) type device, which works under the close infrared spectrometer (NIR) principal. With the help of this principal the Cetane number measurement experiment became very fast and cheap with only 3% error compared to the time consuming expensive motor tests.



Figure 3.7. Zeltex ZX440

3.2.4 Cold Flow Measurement:

A fuel property that is particularly important for the low temperature operability of diesel fuel is the cloud point. The cloud point is the temperature at which a cloud of wax crystals first appears in a liquid upon cooling. Therefore, it is an index of the lowest temperature of the fuel's utility under certain applications. Operating at temperatures below the cloud point for a diesel fuel can result in fuel filter clogging due to the wax crystals. As described in ASTM D 2500, the cloud point is determined by visually inspecting for a haze in the normally clear fuel, while the fuel is cooled under carefully controlled conditions.

A second measure of the low temperature performance of diesel/biodiesel fuels is the pour point. The pour point is the lowest temperature at which a fuel sample will flow. Therefore, the pour point provides an index of the lowest temperature of the fuel's utility for certain applications. The pour point also has implications for the handling of fuels during cold temperatures. The standard procedure for measuring the pour point of fuels is ASTM D 97.

Tanaka MPC-102 (Figure 3.8) was used to determine pour point of fuels. Pour Point measurement is made utilizing a new ASTM test method, namely "Air Pressure Method" (ASTM D6749 on "Standard Test Method for Pour Point of Petroleum Products (Automatic Air Pressure Method 1)), which yields eventually no bias against the conventional test method, repeatability/reproducibility of $1^{o}C$ /$2^{o}C$ and 2-3 times faster determinations. The device can measure according to the ASTM

D6749/D97, ISO 3016 (PP), ASTM D2500, ISO 3015 (CP). Measuring range is +51 ^{o}C to – 40 ^{o}C with tap water of 20 ^{o}C and +51 ^{o}C to – 65 ^{o}C with cooling liquid of -35 ^{o}C. Amount of applied air pressure for pour point detection, to accommodate different sample types: L (low) for diesel fuels, H (high) for lube oils, VH (very high) and UH (ultra high) for residual fuels and similar samples. Testing intervals: 1.0 ^{o}C, 2.5 ^{o}C, 3.0 ^{o}C.



Figure 3.8. Tanaka MPC-102L

3.2.5 Flash Point Measurement:

The flash point is the lowest temperature at which a combustible mixture can be formed above the liquid fuel. It is dependent on both the lean flammability limit of the fuel as well as the vapor pressure of the fuel constituents. The flash point is determined by heating a sample of the fuel in a stirred container and passing a flame over the surface of the liquid. If the temperature is at or above the flash point, the vapor will ignite and an easily detectable flash can be observed (Gerpen et al. 2004).

Tanaka Automated Pensky-Martens Closed Cup Flash Point Tester, model APM-7 (Figure 3.9) was used to determine flash point of test fuels. It is conforming

the standards ISO 2719, ASTM D93, IP 34, ETC. Measuring range is from ambient temperature to 370 ^{o}C.



Figure 3.9. Tanaka APM-7

3.3. Diesel Engine Fuel Requirements

Diesel combustion is the process that occurs when a hydrocarbon fuel, chosen for its ability to auto-ignite, is injected into a volume of air that has been compressed to a high temperature and pressure. When fuel is injected into the turbulent compressed air inside the engine cylinder, it does not ignite immediately. There is a time period called the ignition delay, during which the fuel heats up, vaporizes, mixes with air, and undergoes chemical precombustion reactions that produce the radicals necessary for spontaneous ignition or autoignition. The classical notion of ignition delay calls the heating, vaporization and mixing processes the “physical delay” and the pre-reactions the “chemical delay”. This can be deceptive in that both processes can be, and probably are, occurring simultaneously. After sufficient time has elapsed, ignition will occur spontaneously at multiple locations. Ignition occurs in regions of fuel-air mixture that have fuel-air ratios close to the chemically correct ratio or the stoichiometric ratio. Combustion proceeds very rapidly due to the

backlog of prepared or nearly prepared fuel-air mixtures formed during the ignition delay period. The rapidly rising temperatures and pressure in the cylinder accelerate the combustion in an uncontrolled manner until the backlog is depleted. This portion of the combustion process is usually called premixed combustion. The remainder of the fuel in the spray core is still too rich to burn, so combustion slows down and is controlled by the rate at which the air is entrained and a combustible mixture formed. This portion of the combustion process is called mixing controlled or diffusion burning. Thus, while chemical kinetics dominates the ignition delay, the high temperatures and pressures of the post-ignition gases promote very fast reaction rates that make fuel-air mixing the rate determining process (Gerpen et al. 2004).

Fuel advantages of biodiesel are excellent lubricity, higher oxygen content, no sulfur and aromatic hydrocarbons content, high flash point, and higher biodegradability (Jeong, 2009). Disadvantages are higher cloud point and lower calorific value. Biodiesel has less calorific value than that of diesel fuel due to the oxygen content in their molecules. Fuel properties of biodiesel such as density, kinematic viscosity, heating value, Cetane number and cloud point are highly dependent on fatty acid composition of oil (Pereyra-Irujo, et. al. 2008, Graboski and McCormick, 1998).

The fuel properties of biodiesel promote combustion process and improve exhaust emissions such as particulate matter, carbon monoxide (CO), sulphur oxides (SO_x), volatile organic compounds and unburned hydrocarbons (HC) (Lapuerta et. al. 2008, Ballesteros et. al. 2008, Keskin et. al. 2007, Çaynak et. al. 2008). However, in general, researchers have measured a slight increase in oxides of nitrogen oxides (NO_x) (Hu et. al. 2008, Jha et. al. 2008, Keskin et. al. 2008). In addition, biodiesel does not contribute to global warming due to its closed carbon cycle (Reijnders et. al. 2008, Tan et. al. 2008).

3.3.1. Ignition

One of the most important properties of a diesel fuel is its readiness to autoignite at the temperatures and pressures present in the cylinder when the fuel is injected. The laboratory test that is used to measure this tendency is the Cetane Number Test (ASTM D 613). Fuels with a high cetane number will have short ignition delays and a small amount of premixed combustion since little time is available to prepare the fuel for combustion. The cetane number has been criticized in recent years for not accurately reflecting the autoignition conditions in modern turbocharged engines, particularly with alternative fuels.

3.3.2. Energy Release

The energy content of a fuel is characterized by the amount of heat released when the fuel, starting at ambient conditions, is burned and the products are cooled to ambient conditions. This is defined as the enthalpy of combustion (or the heat of combustion) since the combustion process produces water and energy will be different depending on whether the water is liquid or vapor. Two separate cases are considered. First, if all of the water in the exhaust products is assumed to be liquid, the heat extracted will be the higher heating value or the gross heating value. If all of the water is considered to be vapor, then the heat extracted is the lower heating value or the net heating value. Since engines do not have the ability to condense water in the exhaust, the lower heating value is the most commonly used measure of fuel energy content.

The energy content of the fuel is not controlled during manufacturing. The actual heating value for diesel fuel will vary depending on the refinery in which it was produced, the time of year, and the source of the petroleum feedstock. Beyond these differences, the heating value will depend on the composition of the fuel. Diesel fuels with high percentages of aromatics tend to have high energy contents per gallon even though the aromatics tend to have low heating values per pound. Their higher density more than compensates for their lower energy content on a weight

basis. This is of special importance for diesel engines because fuel is metered to the engine volumetrically. A fuel with lower energy content per gallon will cause the engine to produce less power. Biodiesel fuels do not contain aromatics but they contain fatty acids with different levels of unsaturation. Fuels with more unsaturation tend to have slightly lower energy contents (on a weight basis) while those with greater saturation tend to have higher energy content.

Since diesel engines will inject equal volumes of fuel, most diesel engine operators see a power loss of about 8%. In some cases, the power loss may be even less than this since biodiesel's higher viscosity can decrease the amount of fuel that leaks past the plungers in the diesel fuel injection pump. Tests have shown that the actual efficiency at which the energy in the fuel is converted to power is the same for biodiesel and petroleum-based diesel fuel reference. Therefore, the brake specific fuel consumption (BSFC), the parameter most often used by engine manufacturers to characterize fuel economy will be at least 12.5% higher for biodiesel.

The BSFC is similar to efficiency in that it measures how much fuel may be required to do a certain quantity of work. The smaller the BSFC, the more efficient the engine. However, it does not contain information about the amount of energy that may be available from the fuel, so it cannot be used to make comparisons between engines burning different fuels. The prefix “brake” designates that the power is measured directly at the engine’s output shaft.

The lower heating value (LHV) can be measured by calorimetry or it can be estimated from equations based on the fuel composition. There is some ambiguity in the definition of the thermal efficiency based on whether the higher or lower heating value should be used. Furnace efficiencies tend to be based on the higher heating value. Natural gas is sold on the basis of higher heating value. However, for engines, the normal procedure is to use the lower heating value since the engine does not condense the water vapor in the exhaust gases.

3.3.3. Energy

The density of the fuel is not itself an important parameter for the diesel engine but it is generally related to the fuel's energy content. As a first approximation, hydrocarbon diesel fuels all have about the same energy content per pound. The differences between fuels relate mostly to the density. More dense fuels provide greater energy per gallon and since fuel is sold volumetrically, the higher the density, the greater the potential energy. As mentioned earlier, since biodiesel has a higher density than diesel fuel (0.87-0.88 g/cc compared with 0.84-0.85 g/cc for No. 2 diesel fuel and 0.81 – 0.815 g/cc for No. 1 diesel fuel), biodiesel's 12% lower energy content per pound becomes only 8% less on a galon basis.

3.3.4. Low Temperature Ability

Diesel fuel contains small amounts of long chain hydrocarbons, called waxes that crystallize at temperatures within the normal diesel engine operating range. If temperatures are low enough, these wax crystals will agglomerate and plug fuel filters and prevent engine operation. At a low enough temperature, the fuel will actually solidify. Additives, known as pour point depressants, are used to inhibit the agglomeration of thewax crystals, which then lowers the point at which fuel filter plugging occurs. It is also common to add No. 1 diesel fuel to No. 2 diesel fuel to lower its pour point. No. 1 diesel fuel has a very low level of waxes and dilutes the waxes in No. 2 diesel fuel and thereby lowers the pour point. ASTM D 2500 and D 97 are used to determine the Cloud Point and Pour Points of the fuels, respectively. Other tests are used to measure the tendency of the fuel to plug fuel filters.

3.3.5. Corrosion Resistance

Many of the parts in the diesel fuel injection system are made of high-carbon steels and thus are prone to corrosion when in contact with water. Water damage is the leading cause of premature failure of fuel injection systems. Many diesel engines

are equipped with water separators that cause small water droplets to coalesce until they are large enough to drop out of the fuel flow where they can be removed. Diesel fuel containing excessive water that enters the injection system can cause irreversible damage in a very short time.

ASTM D 2709 is used to measure the total amount of water and sediment in a diesel fuel sample. The method uses a centrifuge to collect the water and limits the amount of water and sediment to 0.05%. Some compounds in diesel fuel, especially sulfur compounds, can be corrosive. Since copper compounds are particularly susceptible to this type of corrosion, copper is used as an indicator of the tendency of the fuel to cause corrosion. ASTM D 130 uses polished copper strips soaked in the fuel to characterize the tendency to corrode metals. Some tarnish is typically allowed, but corrosion causes the fuel to fail the test.

3.3.6. Wearing

Diesel fuel filters are designed to capture particles that are larger than 10 microns in size. Some newer engines are even equipped with filters that capture particles as small as 2 microns. These filters should stop foreign materials from entering the fuel injection they can undergo chemical changes that form compounds that are insoluble in the fuel. These compounds form varnish deposits and sediments that can plug orifices and coat moving parts causing them to stick. Several test procedures have been developed that attempt to measure the tendency of diesel fuels to produce these sediments, such as ASTM D 2274, but none have gained the acceptance needed to be included in the diesel fuel specification (ASTM D 975). When diesel fuel burns, it should be converted entirely to carbon dioxide and water vapor. Inorganic materials present in the fuel may produce ash that can be abrasive and contribute to wear between the piston and cylinder. ASTM D 482 is used to characterize ash from diesel fuels. The ASTM specification for biodiesel, D 6751, requires that ASTM D 874 be used. This method measures sulfated ash, which is specified because it is more sensitive to ash from sodium and potassium. These metals are likely to be the main sources for ash in biodiesel. When fuel is exposed to

high temperatures in the absence of oxygen, it can pyrolyze to a carbon-rich residue. While this should not occur in the cylinder of a properly operating engine, some injection systems have the potential to create a region within the injection nozzle where this residue can collect and limit the range of motion of moving parts. Various test procedures such as ASTM D 189, D 524, and D 4530 have been developed as an attempt to predict the tendency of a fuel to form in-cylinder carbon deposits. Unfortunately, it is very difficult to reproduce in-cylinder conditions in a test, so the correlation of these procedures to actual engine deposits is limited. Diesel fuel injection systems have very closely fitting parts that are subjected to high loads. These parts require lubrication to prevent rapid wear. All diesel injection systems rely on the fuel itself to provide this lubrication. While the mechanism is not fully understood, it is known that as refiners reduce the sulfur content of diesel fuel the ability of the fuel to provide the necessary lubrication decreases. The property that characterizes the ability of the fuel to lubricate is the lubricity. Several tests are commonly used to measure lubricity but they have not been accepted or required as part of the ASTM specification for diesel fuel.

3.3.7. Pollution

Under ideal circumstances, all of the carbon in the diesel fuel will burn to carbon dioxide and all of the hydrogen will burn to water vapor. In most cases, virtually all of the fuel does follow this path. However, if sulfur is present in the fuel, it will be oxidized to sulfur dioxide and sulfur trioxide. These oxides of sulfur can react with water vapor to form sulfuric acid and other sulfate compounds. The sulfates can form particles in the exhaust and elevate the exhaust particulate level. In 1993, the Environmental Protection Agency mandated that diesel fuel should contain no more than 500 ppm of sulfur. This was a factor of 10 reduction in sulfur level and greatly reduced sulfur as a source of exhaust particulate. In 2006, the EPA has mandated a new reduction in sulfur to 15 ppm. This will eliminate sulfur as a component of exhaust particulate and allow the introduction of catalytic after treatment on diesel engines. Sulfur is a powerful catalyst poison and limits the

options available for controlling emissions on future engines. Aromatics are a class of hydrocarbon compounds that are characterized by stable chemical structures. They are usually present in diesel fuel at levels between 30 to 35%. They are desired by diesel engine operators because they provide greater energy per gallon of fuel but they are believed to contribute to higher particulate and NO_x emissions, and tend to have lower cetane values. In the early 1990s, CARB implemented standards that limited the aromatic content of diesel fuels sold in California to 10%. CARB later allowed the aromatic content to be higher if fuel producers could show that their fuels produced equivalent or lower emissions than the low aromatic fuel. Biodiesel contains no aromatics. It is also naturally low in sulfur. Biodiesel from soybean oil and most vegetable oils contain essentially no sulfur but some sulfur has been found in biodiesel produced from animal fats.

3.3.8. Viscosity

Fuel viscosity is specified in the standard for diesel fuel within a fairly narrow range. Hydrocarbon fuels in the diesel boiling range easily meet this viscosity requirement. Most diesel fuel injection systems compress the fuel for injection using a simple piston and cylinder pump called the plunger and barrel. In order to develop the high pressures needed in modern injection systems, the clearances between the plunger and barrel are approximately one ten-thousandth of an inch. In spite of this small clearance, a substantial fraction of the fuel leaks past the plunger during compression. If fuel viscosity is low, the leakage will be enough to cause a significant power loss for the engine. If fuel viscosity is high, the injection pump will be unable to supply sufficient fuel to fill the pumping chamber. Again, the effect will be a loss in power. If fuel viscosity is extremely excessive, as is the case with vegetable oils that have not been transesterified, there will be a degradation of the spray in the cylinder causing poor atomization and the production of black smoke.

3.3.9. Safety

Diesel engine operators are accustomed to treating diesel fuel as is it was nonflammable. The volatility of diesel fuel is low enough that the air-vapor mixture above the fuel is below the flammability limit. The property that characterizes this behavior is the flashpoint. The temperature at which the fuel will give off enough vapor to produce a flammable mixture is the flashpoint. This temperature is 51 °C to 60°C for diesel fuel.

3.4. Compression Ignition Engine Test Rig

Engine performance tests were conducted on a commercial four cylinder, four-stroke, naturally aspirated, water-cooled direct injection compression ignition engine with a 89 kW maximum power at 3200 rpm engine speed and has 295 Nm maximum torque at 1800 rpm engine speed. Technical specifications of engine were presented in Table 3.4. Before the tests, the engine was operated for 15 minutes with diesel fuel to reach the operation temperature. Test fuels were tested from 1200 to 3200 rpm with an interval of 200 rpm at full load condition. A hydraulic dynamometer was used for determination of torque and power output. Schematic representation of experimental setup was presented in Figure 3.10.

Table 3.4. Technical specifications of the test engine

Brand	Mitsubishi Canter
Model	4D34-2A
Configuration	In line 4
Type	Direct injection diesel with glow plug
Displacement	3907cc
Bore	104mm
Stroke	115mm
Power	89kW @ 3200rpm
Torque	295Nm @ 1800rpm
Oil Cooler	Water cooled
Air Cleaner	Paper element type
Weight	325kg

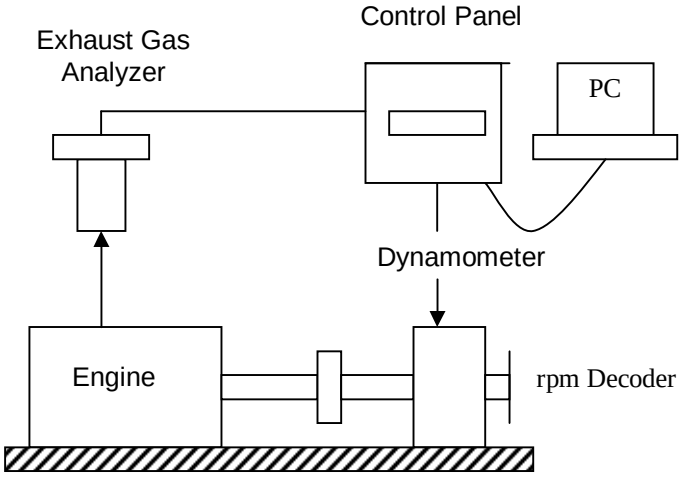


Figure 3.10. Schematic representation of experimental setup

The engine torque was measured by the help of a hydraulic dynamometer. Table 3.5 shows technical specifications of the dynamometer.

Table 3.5. Technical specifications of the dynamometer

Torque range	0-1700 Nm
Speed range	0-7500 rpm
Body weight	45 kgf
Total weight	110 kgf
Body diameter	350 mm
Torque arm length	350mm

The speed sensor used to detect prime mover speed is the magnetic pickup (MPU). When a magnetic material (usually a gear tooth driven by the prime mover) passes through the magnetic field at the end of the magnetic pickup, a voltage is developed. The frequency of this voltage is translated by the speed into a signal which accurately depicts the speed of the prime mover. S type load cell is used to measure the torque of dynamometer (Stainless steel which has a sensivity of 1/3000. Dynamometer control unit was used for receiving and collecting all the data that was used by the system.

3.5. Exhaust Emission Measurements

TESTO 350 XL gas analyzer is used to measure exhaust emissions. Emission data was collected by the help of a computer program. Measurement accuracy of the gas analyzer is ±10 ppm for CO, 1% for CO_2 and ±1 ppm for NO_x. Measurement capacity of the device is 0-10000 ppm for CO, 0-50% for CO_2 emission and 0-3000 ppm for NO_x.

4. RESULTS AND DISCUSSION

4.1. Effects of Magnesium Oxide (MgO) Nanoparticle Additive on Diesel Fuel

4.1.1. Fuel Properties

The analysis of test fuels was conducted at the Çukurova University Mechanical Engineering Department Automotive Engineering Laboratories. Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of diesel and modified diesel fuels were given in Table 4.1. Also European petrodiesel standard EN 590 was given in Table 4.1.

Table 4.1. Fuel Properties of Diesel and Modified Diesel Fuels

Property	Units	EN 590	Diesel	25 ppm MgO	50 ppm MgO	100 ppm MgO
Density at 15°C	kg/m³	820-845	833	833	834	834
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	2.86	2.88	2.90
Flash point	°C	Min 55	58.5	63.5	63.5	62.5
Cetane number	-	Min 51	56	51.1	45.7	42.6
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) MgO nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was not changed considerably with the addition of MgO nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of diesel fuel only increased from 2.85 mm^2/s to 2.86 mm^2/s, 2.88 mm^2/s and 2.90 mm^2/s at the dosage of 25, 50 and 100 ppm MgO nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the MgO nanoparticles addition. At the dosage of 25, 50 and 100 ppm it was increased to 63.5 °C, 63.5 °C and 62.5 °C respectively. The flash point of the fuel gives an indication of the

volatility of a fuel. The lower the volatility the higher the flash and fire points. Higher flash point temperatures are desirable for safe handling of the fuel. According to European petrodiesel standard EN 590 for diesel fuel a minimum flash point of 55 °C is required for safety. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm MgO nanoparticles addition to diesel fuel) can be done safely according to base fuel (diesel fuel).

Cetane number of the diesel fuel showed decreasing trend with the addition of MgO nanoparticles. It was decreased to 51.1, 45.7 and 42.6 at the dosage of 25, 50 and 100 ppm MgO nanoparticles addition respectively. Cetane number is the ignition quality of a fuel. Decrease in the cetane number means decrease in the ignition quality of the fuel which will lead to poor combustion of the fuel in the combustion chamber. An adequate cetane number is required for good engine performance. According to European petrodiesel standard EN 590 for diesel fuel a minimum cetane number of 51 is required for good combustion. Cetane number (51.1) of the modified fuel is in the limits of EN 590 when the dosage of MgO nanoparticles addition is 25 ppm. At the dosage of 50 and 100 ppm, cetane numbers (45.7 and 42.6) of the modified fuels are outside of the EN 590 range.

The temperature at which crystal formation is extensive enough to prevent free pouring of fluid is determined by measurement of its pour point (PP). If pour point of a fuel is not low enough, some concerns with storing, transferring can occur. Addition of 25, 50 and 100 ppm MgO nanoparticles to diesel fuel did not show significant effect on the pour point.

4.1.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.1. Generally power output values reduced with the increased dosage of MgO nanoparticle addition in the diesel fuel at high engine speeds. The characteristics of power curve were not changed according to dosage of the additive. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power reduction according to diesel fuel result is 12%, 17% and

20% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power reduction was obtained at 2600 rpm engine speed for the all test fuels. The average reduction is 3.8%, 6.1% and 8.2% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. The reduction can be resulted from incomplete combustion of the fuel due to low cetane numbers of modified fuels.

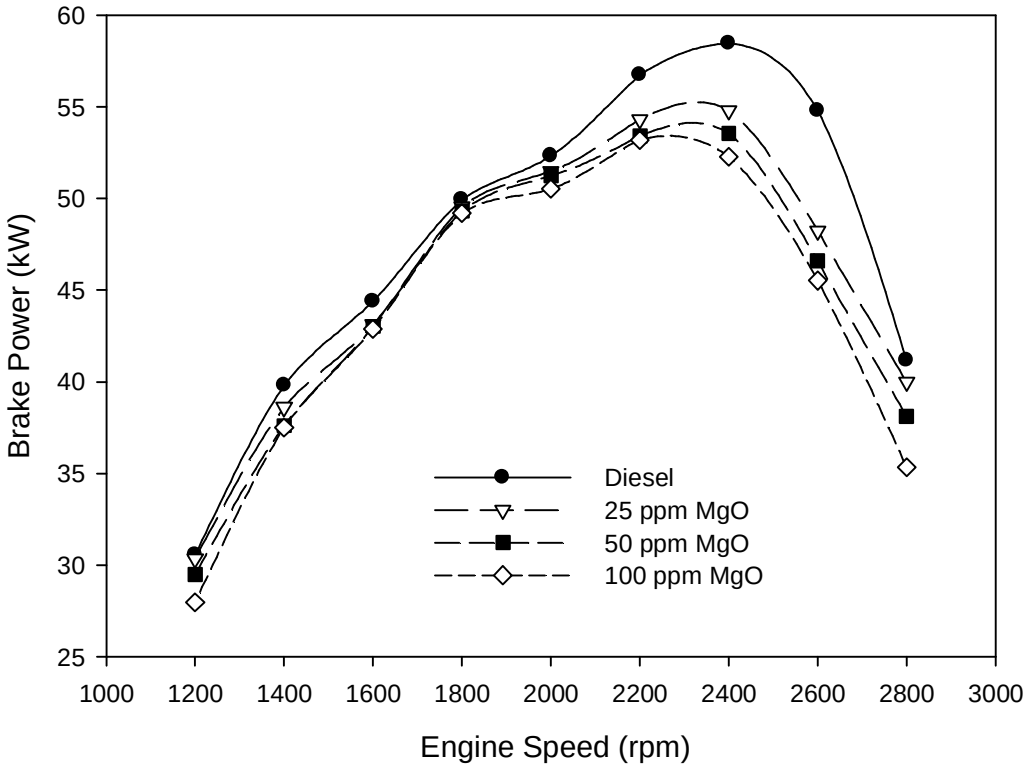


Figure 4.1. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.2. Generally torque output values reduced with the increased dosage of MgO nanoparticle addition in the diesel fuel. The characteristics of torque curve were not changed according to dosage of the additive. The maximum torque values for all fuels were obtained at an engine speed of 1400-1600 rpm. The maximum torque output reduction according to diesel fuel result is 10%, 13.3% and 17.1% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The value of the torque reduction amount is higher at high engine speeds (average 13.4 % at 2600 rpm) than that of at

lower engine speeds (average 2.2 % at 1200 rpm). The maximum torque reduction was obtained at 2600 rpm engine speed for the all test fuels. The average reduction is 4.5%, 5.5% and 6.4% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

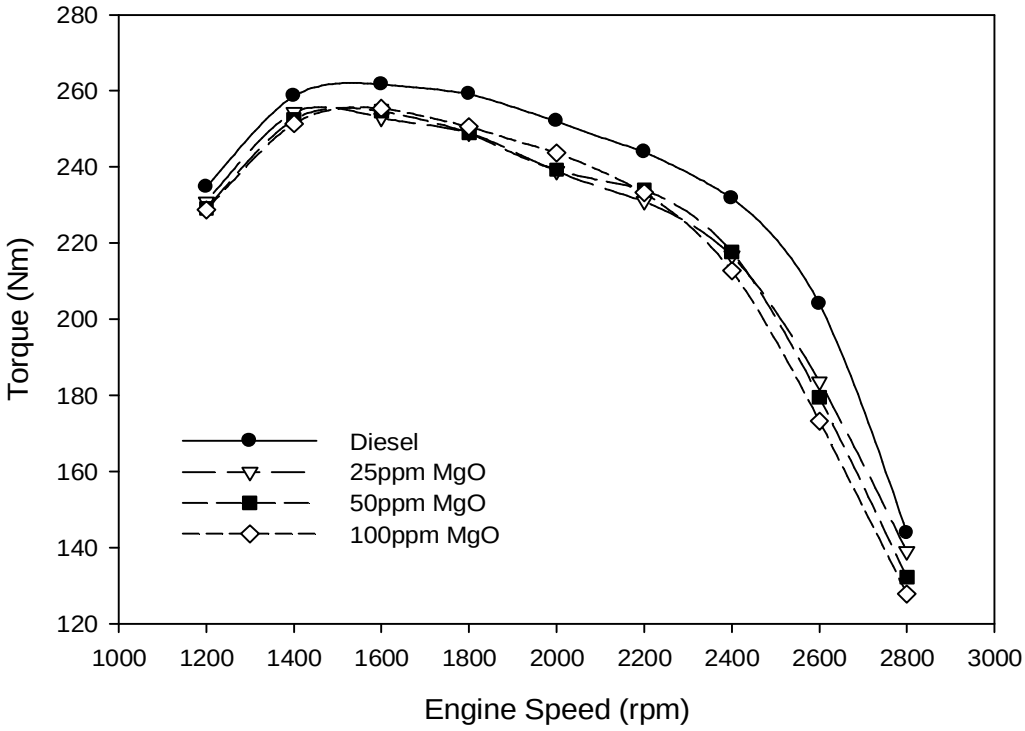


Figure 4.2. Torque output versus engine speed for the test fuels

The variation in specific fuel consumption (SFC) with engine speed for test fuels is presented in Figure 4.3. Minimum SFC values of the test fuels were measured at the engine speed range of 2400 rpm where the maximum engine power was obtained. The SFC values of the modified fuels (25, 50 and 100 ppm MgO nanoparticles addition to diesel fuel) with respect to base fuel (diesel fuel) were decreased at higher engine speed especially between 2400 and 2800 rpm and increased at lower engine speed particularly between 1200 and 1800 rpm. The maximum specific fuel consumption reduction according to diesel fuel result is 3.3%, 4.8% and 6.7% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively at the engine speed of 2800 rpm. The maximum increment is 0.8%, 2% and 5.8% at the addition dosage of 25, 50 and 100 ppm respectively at

the engine speed of 1400 rpm. The average change in the SFC values of all the test fuels is under 0.6 % which refers to there is not noticeable change in the SFC values averagely.

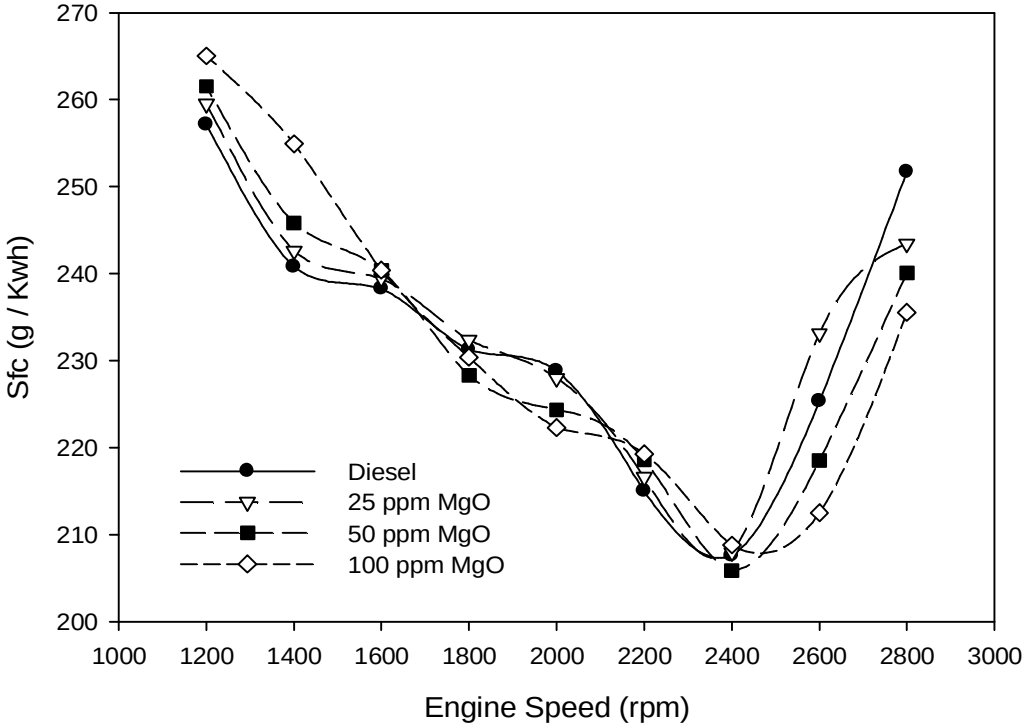


Figure 4.3. Specific fuel consumption versus engine speed for the test fuels

4.1.3. Exhaust Emissions

Figure 4.4 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. In comparison with diesel fuel, CO emission values of modified fuels (50 and 100 ppm MgO nanoparticles addition to diesel fuel) was increased at high engine speeds (2000-2800 rpm) and decreased at lower engine speeds for all modified fuels (25, 50 and 100 ppm MgO nanoparticles addition to diesel fuel). The maximum CO emission reduction according to diesel fuel result is 17.6%, 30.6% and 28% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO emission reduction was obtained at 1200 rpm engine speed for the all test fuels. The maximum

average reduction is 12.2% according to base fuel (diesel fuel) at the MgO nanoparticle addition dosage of 25 ppm.

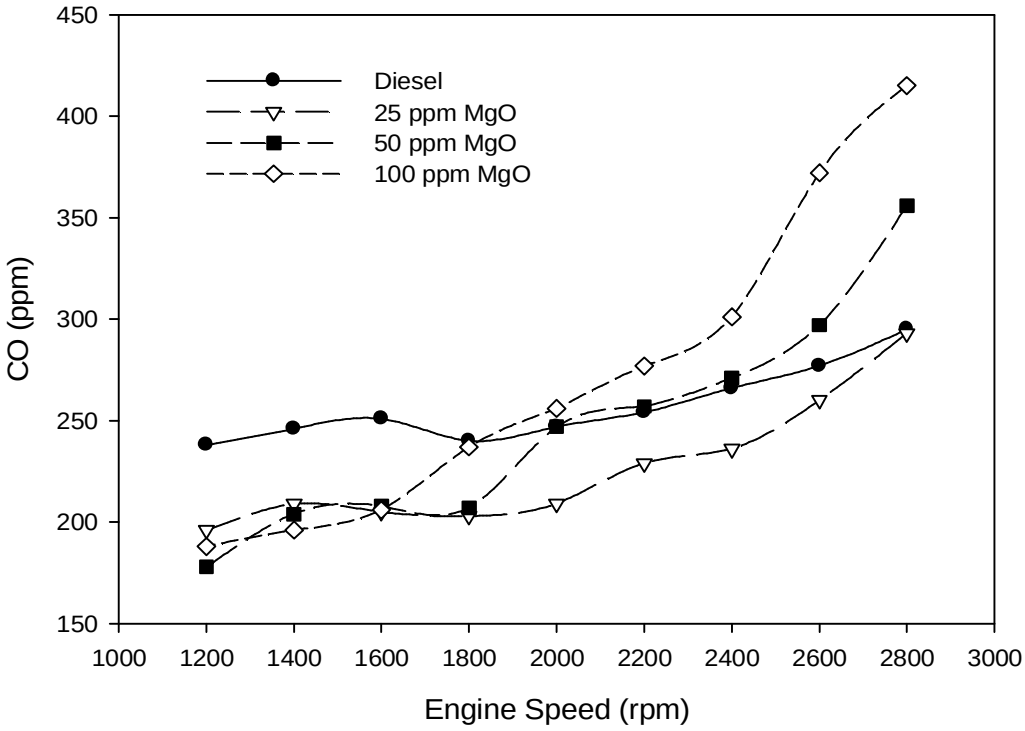


Figure 4.4. CO emission values of test fuels

Figure 4.5 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. The maximum CO_2 emissions were measured with diesel fuel. CO_2 emissions were reduced with the increase in the dosage of the MgO nanoparticle addition. The maximum carbon dioxide emission reduction according to diesel fuel result is 6%, 8.5% and 29.4% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum carbon dioxide emission reduction was obtained at 2800 rpm engine speed for the all test fuels. The average reduction is 1.9%, 6.6% and 13.6% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

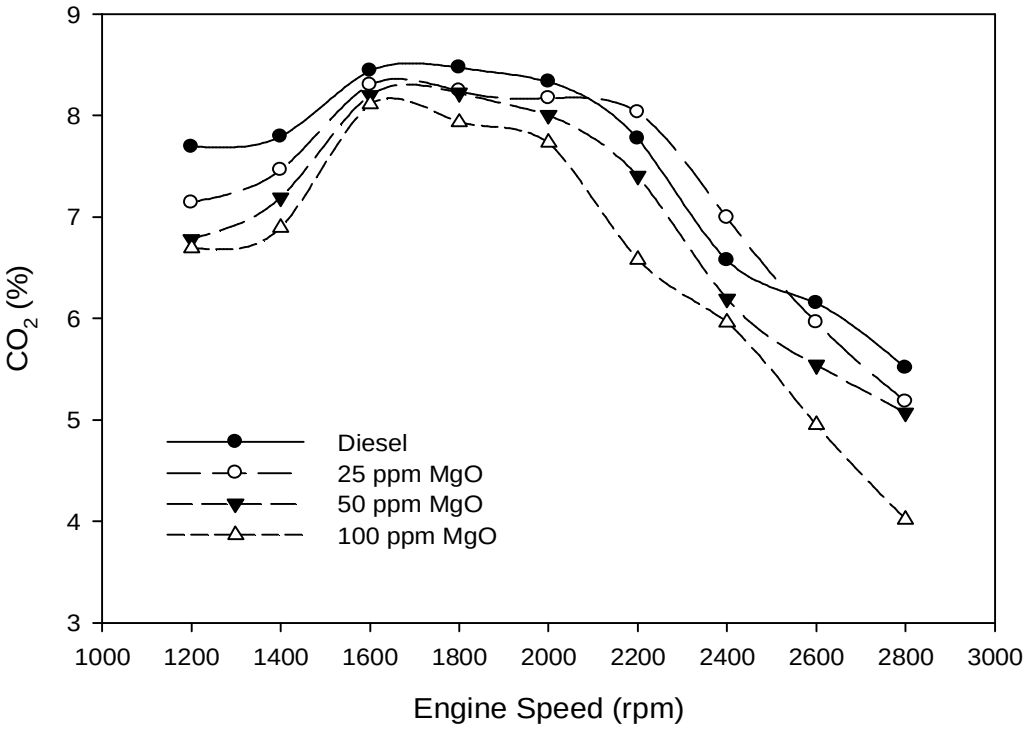


Figure 4.5. CO_2 emission values of test fuels.

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.6. The maximum NO_x emissions were measured with diesel fuel. NO_x emissions were reduced with the increase in the dosage of the MgO additive. The maximum nitrogen oxides emission reduction according to diesel fuel result is 4%, 12.3% and 37% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 2800 rpm engine speed for the all test fuels. The average reduction is 3.1%, 8.9% and 16.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. The reductions in NO_x emission is due to complete combustion of modified fuels with the help of catalyst effect of MgO nanoparticle addition which promotes heat transfer in the combustion chamber.

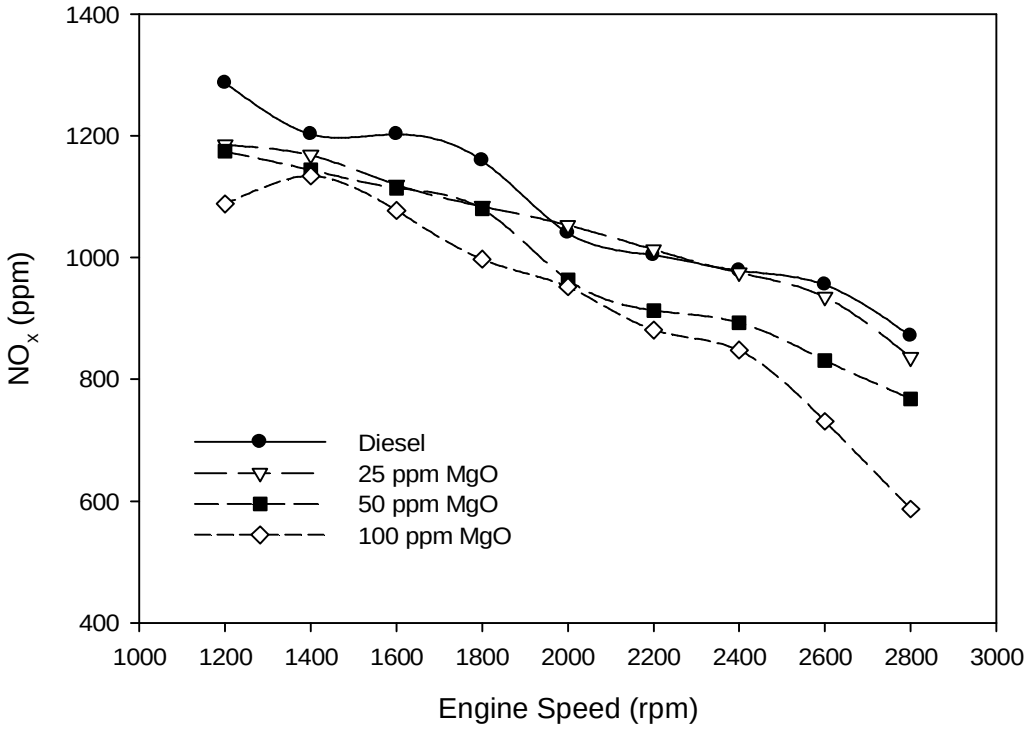


Figure 4.6. NO_x emission values of test fuels.

4.2. Effects of Silicon Oxide (SiO_2) Nanoparticle Additive on Diesel Fuel

4.2.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of diesel and modified diesel fuels were given in Table 4.2. Also European petrodiesel standard EN 590 was given in Table 4.2.

Table 4.2. Fuel Properties of Diesel and Modified Diesel Fuels

Property	**Units**	**EN 590**	**Diesel**	**25 ppm SiO_2**	**50 ppm SiO_2**	**100 ppm SiO_2**
Density at 15°C	kg/m³	820-845	833	832	834	833
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	2.84	2.88	2.92
Flash point	°C	Min 55	58.5	63.5	64.5	64.5
Cetane number	-	Min 51	56	56.1	56.8	58.5
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) SiO_2 nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was not changed considerably with the addition of SiO_2 nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.84 mm^2/s, 2.88 mm^2/s and 2.92 mm^2/s at the dosage of 25, 50 and 100 ppm SiO_2 nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the SiO_2 nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 63.5 °C, 64.5 °C and 64.5 °C respectively. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm SiO_2 nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed increasing trend with the addition of SiO_2 nanoparticle. It was increased to 56.1, 56.8 and 58.5 at the dosage of 25, 50 and 100 ppm SiO_2 nanoparticles addition respectively. Higher cetane numbers help ensure good cold start properties and minimize the formation of white smoke. Cetane numbers of the all modified fuels are in the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm silicon oxide nanoparticles to diesel fuel, as shown in Table 4.2 abstracting the measurement of these properties.

4.2.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.7. Generally power output values reduced with the increased dosage of silicon oxide nanoparticle addition in the diesel fuel at high engine speeds. The characteristics of power curve were not changed, according to dosage of the additive. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power reduction according to diesel fuel result is 13.9%, 15.3% and 17.1% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The increase in the dosing level of the additive results increase in the brake power reduction values. The maximum brake power reduction was obtained at 2800 rpm engine speed for the all test fuels. The average reduction is 4.3%, 4.8% and 4.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

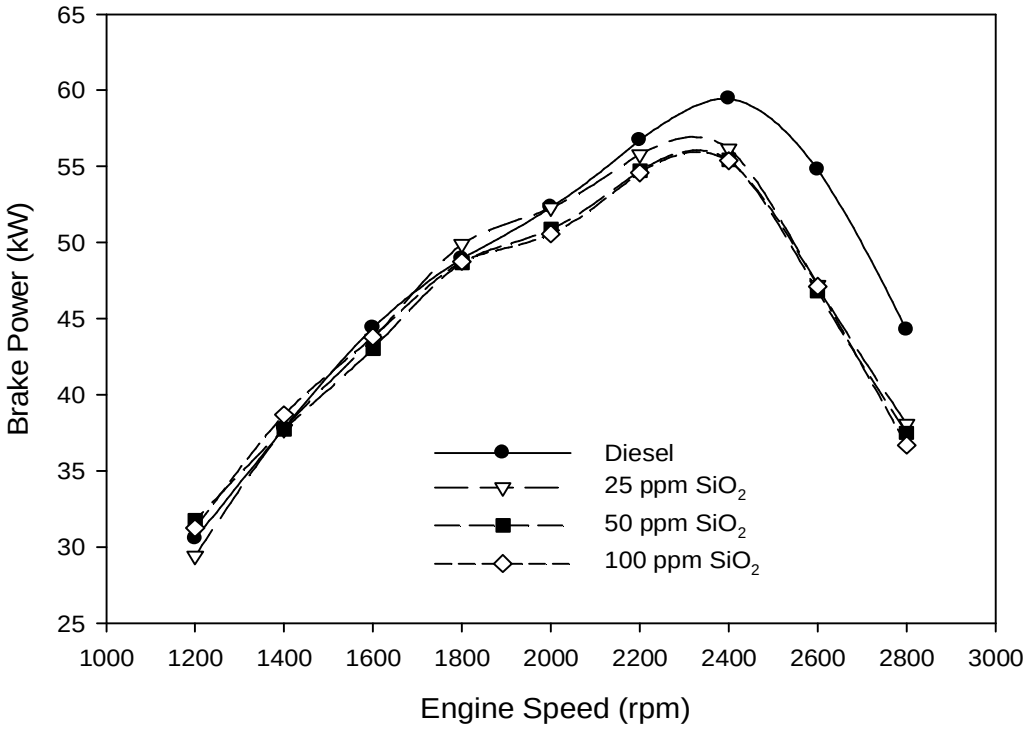


Figure 4.7. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.8. Generally torque output values reduced with the increased dosage of SiO_2 nanoparticle addition in the diesel fuel. The characteristics of torque curve were not changed, according to dosage of the additive. The maximum torque values for all fuels were obtained at an engine speed of 1400-1600 rpm. The maximum torque output reduction according to diesel fuel result is 14.1%, 13.9% and 15.1% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The value of the torque reduction amount is higher at high engine speeds (average 14.3 % at 2600 rpm) than that of at lower engine speeds (average 1.6 % at 1400 rpm). The maximum torque reduction was obtained at 2600 rpm engine speed for the all test fuels. The average reduction is 4.2%, 5% and 5.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

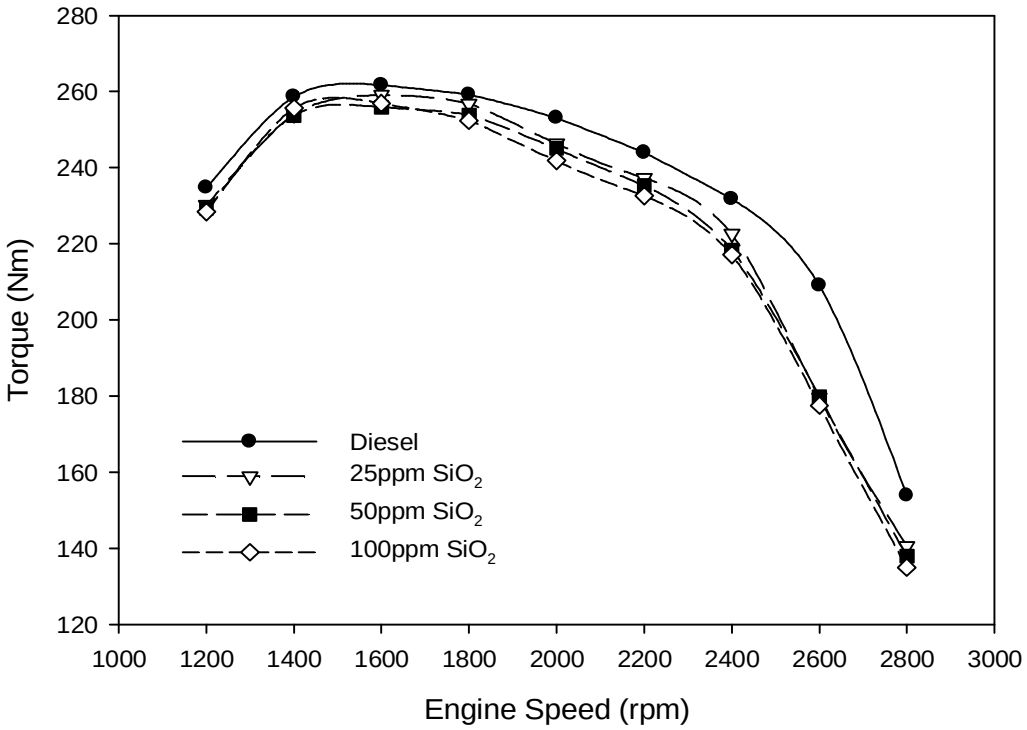


Figure 4.8. Torque output versus engine speed for the test fuels

4.2.3. Exhaust Emissions

Figure 4.9 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. In comparison with diesel fuel, CO emissions values of modified fuels was increased at high engine speeds (2600-2800 rpm) and decreased at lower engine speeds (1200-2600 rpm) for all modified fuels (25, 50 and 100 ppm SiO_2 nanoparticles addition to diesel fuel). The maximum CO emission reduction according to diesel fuel result is 10.4%, 14.1% and 19.7% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO emission reduction was obtained at 1800 rpm engine speed for 25 and 50 ppm additive and at 1200 rpm engine speed for 100 ppm additive. The maximum average reduction is 4.4%, 4%, 9.1% according to base fuel (diesel fuel) at the SiO_2 nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

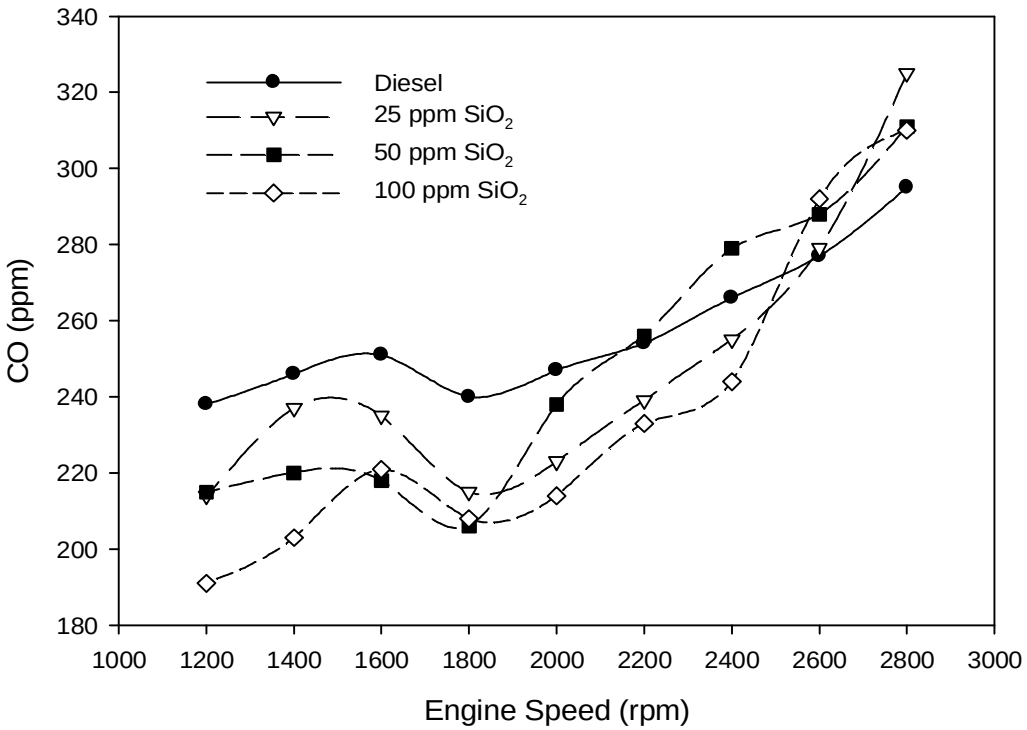


Figure 4.9. CO emission values of test fuels

Figure 4.10 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. The maximum CO_2 emissions were measured with diesel fuel. The maximum carbon dioxide emission reduction according to diesel fuel result is 9.6%, 12.7% and 10.5% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum carbon dioxide emission reduction was obtained at between 2800 and 2600 rpm engine speeds for the all test fuels. The average reduction is 3%, 6.4% and 4% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

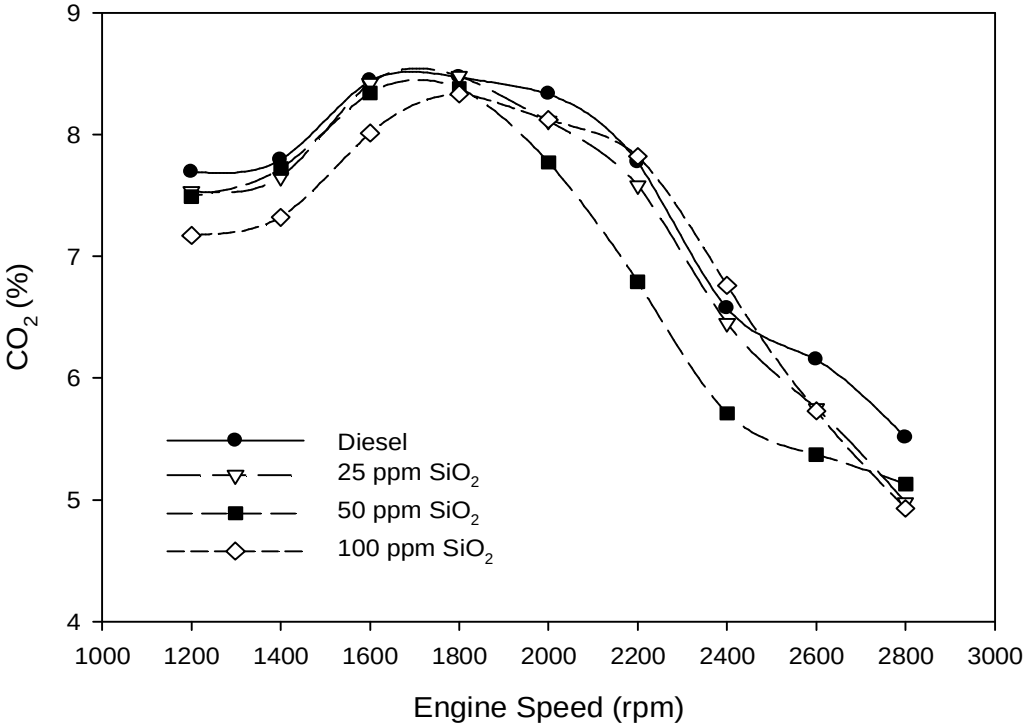


Figure 4.10. CO_2 emission values of test fuels.

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.11. The maximum NO_x emissions were measured with diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 5.4%, 13.6% and 10% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at between 2600 and 2800 rpm engine speeds for the all test fuels. The average reduction is 1%, 7% and

3% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Dosing level of 50 ppm Silicon oxide addition gave the best result for decreasing NO_x emissions. The reductions in NO_x emission is due to complete combustion of modified fuels with the help of catalyst effect of SiO_2 nanoparticle addition which promotes heat transfer in the combustion chamber.

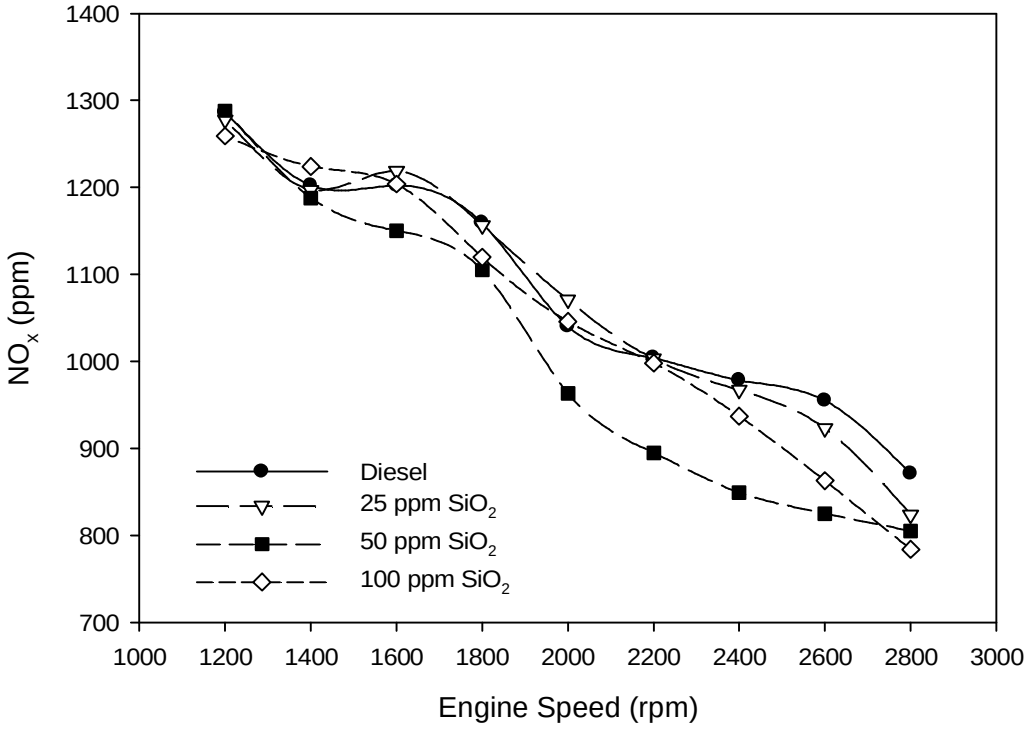


Figure 4.11. NO_x emission values of test fuels.

4.3. Effects of Aluminum Oxide (Al_2O_3) Nanoparticle Additive on Diesel Fuel

4.3.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of diesel and modified diesel fuels were given in Table 4.3. Also European petrodiesel standard EN 590 was given in Table 4.3.

Table 4.3. Fuel Properties of Diesel and Modified Diesel Fuels

Property	Units	EN 590	Diesel	25 ppm Al_2O_3	50 ppm Al_2O_3	100 ppm Al_2O_3
Density at 15°C	kg/m³	820-845	833	834	833	832
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	2.83	3.06	3.08
Flash point	°C	Min 55	58.5	65.5	65.5	66.5
Cetane number	-	Min 51	56	48.8	42.6	39.3
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) Al_2O_3 nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was a little bit increased with the addition of Al_2O_3 nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.83 mm^2/s, 3.06 mm^2/s and 3.08 mm^2/s at the dosage of 25, 50 and 100 ppm Al_2O_3 nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the Al_2O_3 nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 65.5 °C, 65.5 °C and 66.5 °C respectively. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm Al_2O_3 nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of Al_2O_3 nanoparticle. It was decreased to 48.8, 42.6 and 39.3 at the dosage of 25, 50

and 100 ppm Al_2O_3 nanoparticles addition respectively. Cetane numbers of the all modified fuels are outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm aluminum oxide nanoparticles to diesel fuel, as shown in Table 4.3 abstracting the measurement of these properties.

4.3.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.12. Generally power output values reduced with the increased dosage of aluminum oxide nanoparticle addition in the diesel fuel at high engine speeds. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power reduction according to diesel fuel result is 9.8%, 5.5% and 15.5% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power reduction was obtained at 2800 rpm engine speed for 25 and 100 ppm and at 2600 rpm engine speed for 50 ppm aluminum oxide addition dosage. The average reduction is 3.2%, 2.4% and 3.3% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

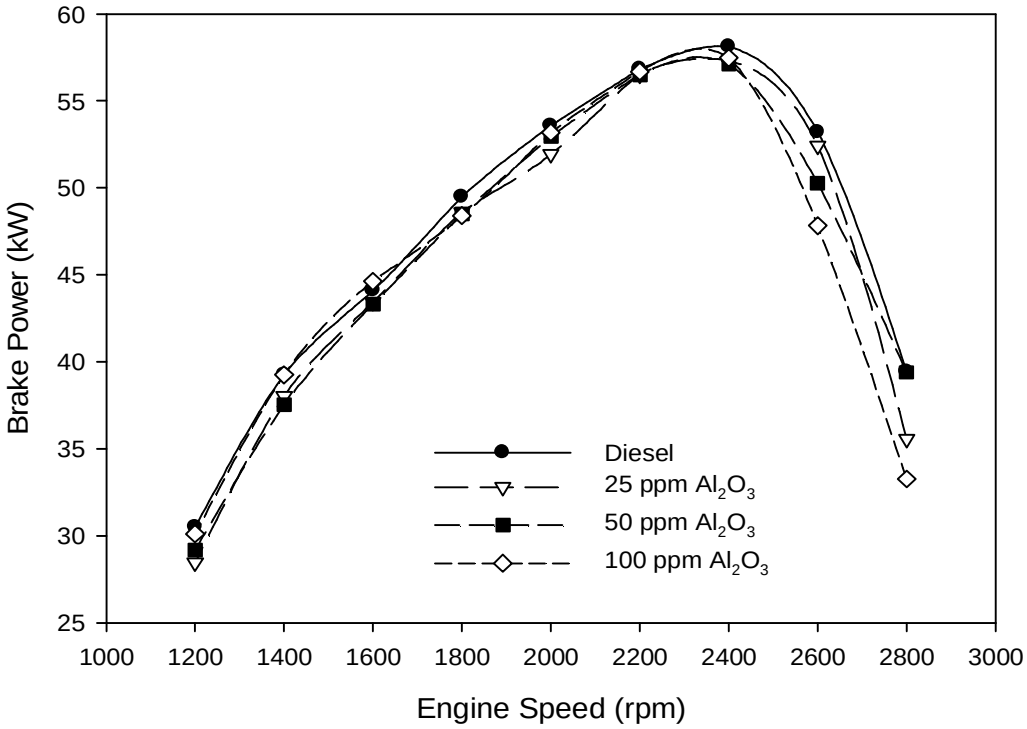


Figure 4.12. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.13. Generally torque output values reduced with the increased dosage of Al_2O_3 nanoparticle addition in the diesel fuel at high engine speeds (2400-2600 rpm). The maximum torque values for all fuels were obtained at an engine speed of 1400-1600 rpm. The maximum torque output reduction according to diesel fuel result is 10.3%, 7.8% and 16.9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The value of the torque reduction amount is higher at high engine speeds (average 10.2 % at 2800 rpm) than that of at lower engine speeds (average 1 % at 1400 rpm). The maximum torque reduction was obtained at 2800 rpm engine speed for 25 and 100 ppm and at 2600 rpm engine speed for 50 ppm aluminum oxide addition dosage. The average reduction is 2.4%, 3.2% and 4.2% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average torque reduction values increased with the increased dosage of aluminum oxide nanoparticle addition in the diesel fuel.

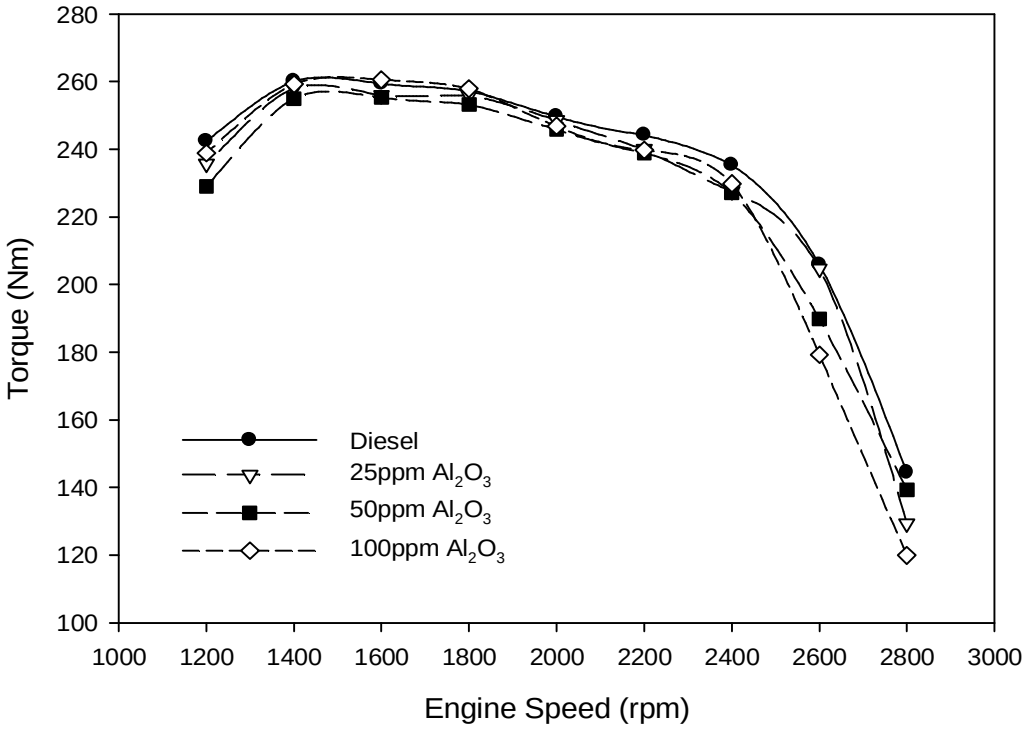


Figure 4.13. Torque output versus engine speed for the test fuels

4.3.3. Exhaust Emissions

Figure 4.14 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. Al_2O_3 nanoparticle addition dosage of 25 ppm and 50 ppm decreased the CO emissions and addition dosage of 100 ppm increased the CO emissions values with respect to diesel fuel. The maximum CO emission reduction according to diesel fuel result is 15.8%, 14.3% for the modified fuels at the nanoparticle addition dosage of 25, 50 ppm respectively. The maximum CO emission reduction was obtained at 2000 rpm engine speed. The maximum CO emission increase according to diesel fuel result is 20.1% for the modified fuel at the nanoparticle addition dosage of 100 ppm. The maximum CO emission increase was obtained at 2800 rpm engine speed. The average reduction is 10.5% and 8.8% according to base fuel (diesel fuel) at the Al_2O_3 nanoparticle addition dosage of 25, 50 ppm respectively. The average increase is 8.4% according to base fuel at the addition dosage of 100 ppm.

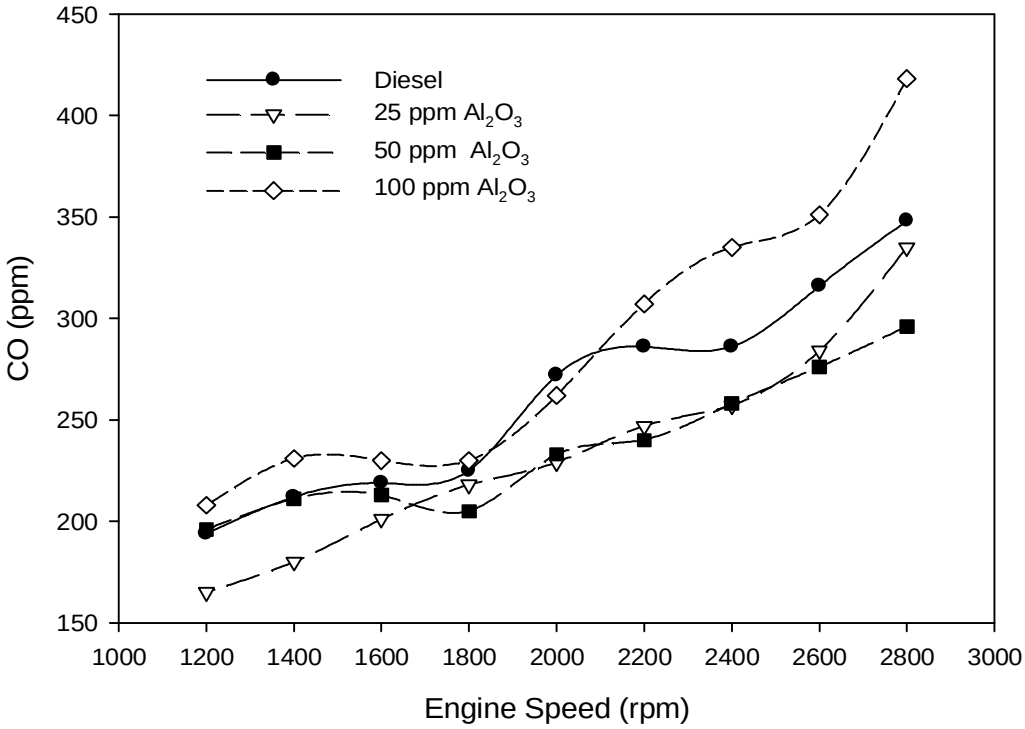


Figure 4.14. CO emission values of test fuels

Figure 4.15 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. Al_2O_3 nanoparticle addition dosage of 25 ppm and 100 ppm decreased the CO_2 emissions and addition dosage of 50 ppm increased the CO_2 emissions values with respect to diesel fuel. The maximum CO_2 emission reduction according to diesel fuel result is 9.1%, 19% for the modified fuels at the nanoparticle addition dosage of 25, 100 ppm respectively. The maximum CO_2 emission reduction was obtained at 1600 rpm engine speed for 25 ppm addition and at 2800 rpm engine speed for the 100 ppm addition dosage. The maximum CO_2 emission increase according to diesel fuel result is 9% for the modified fuel at the nanoparticle addition dosage of 50 ppm. The maximum CO_2 emission increase was obtained at 2200 rpm engine speed. The average reduction is 0.7% and 1.2% according to base fuel (diesel fuel) at the Al_2O_3 nanoparticle addition dosage of 25, 100 ppm respectively. The average increase is 3% according to base fuel at the addition dosage of 50 ppm.

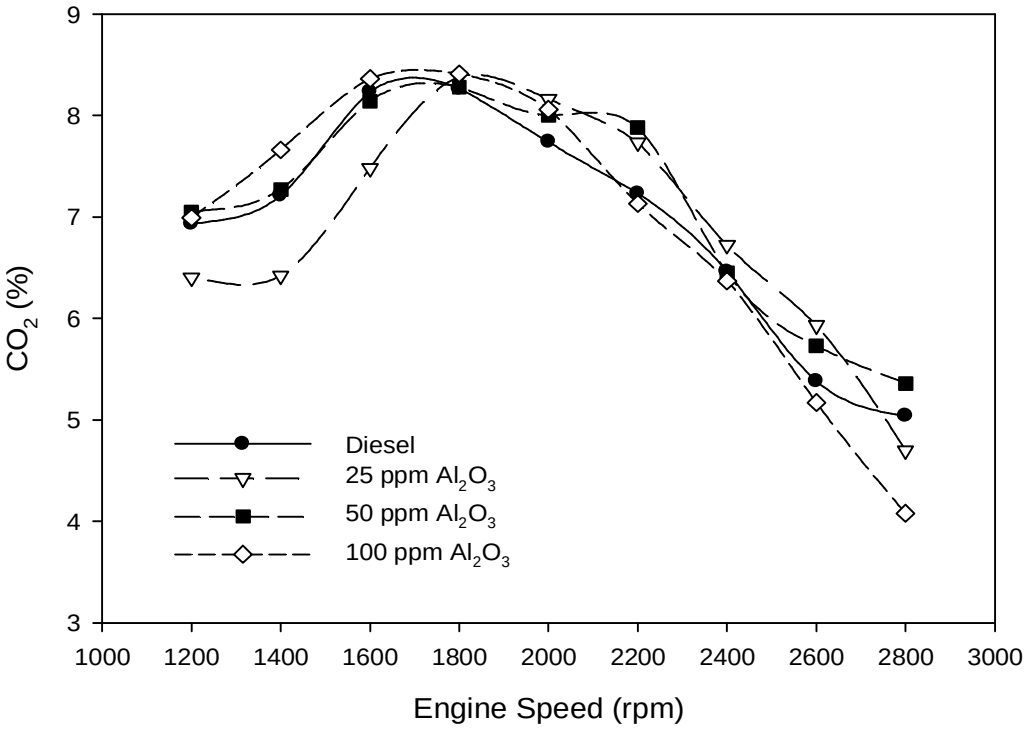


Figure 4.15. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.16. The maximum NO_x emissions were measured with modified fuel with the Al_2O_3 addition dosage of 25 ppm. The nitrogen oxides emissions values of diesel fuel was commonly increased with the addition of aluminum oxide nanoparticles. The maximum nitrogen oxides emission increase according to diesel fuel result is 13%, 6.4% and 6.4% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission increase was obtained at between 2600 and 2400 rpm engine speeds for the all test fuels. The average increase is 4%, 1.4% and 0.5% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

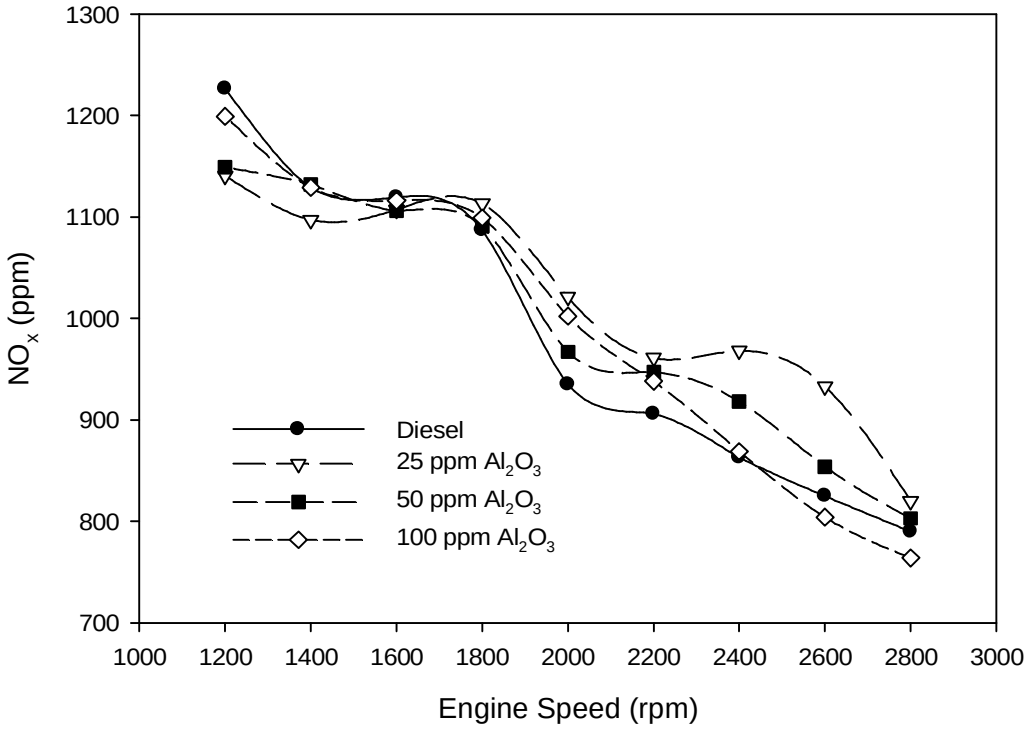


Figure 4.16. NO_x emission values of test fuels

4.4. Effects of Zinc Oxide (ZnO) Nanoparticle Additive on Diesel Fuel

4.4.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Obtained fuel properties of diesel and modified diesel fuels were given in Table 4.4. Also European petrodiesel standard EN 590 was given in Table 4.4.

Table 4.4. Fuel Properties of Diesel and Modified Diesel Fuels

Property	Units	EN 590	Diesel	25 ppm ZnO	50 ppm ZnO	100 ppm ZnO
Density at 15°C	kg/m³	820-845	833	834	834	832
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	2.80	2.81	2.83
Flash point	°C	Min 55	58.5	63.5	64.5	65.5
Cetane number	-	Min 51	56	54	47.9	42.3
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) ZnO nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was not changed considerably with the addition of ZnO nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.80 mm^2/s, 2.81 mm^2/s and 2.83 mm^2/s at the dosage of 25, 50 and 100 ppm ZnO nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the ZnO nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 63.5 °C, 64.5 °C and 65.5 °C respectively. The increase in the dosing level of the addition led to increase in the flash point of the diesel fuel. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm zinc oxide nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of ZnO nanoparticle. It was decreased to 54, 47.9 and 42.3 at the dosage of 25, 50 and 100 ppm ZnO nanoparticles addition respectively. Cetane number of the modified fuels with the ZnO nanoparticle addition dosage of 25 ppm in the limits, 50 and 100 ppm are outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm zinc oxide nanoparticles to diesel fuel, as shown in Table 4.4 abstracting the measurement of these properties.

4.4.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.17. Generally power output values increased with the increased dosage of zinc oxide nanoparticle addition in the diesel fuel at high engine speeds (between 2200 and 2800 rpm) and decreased with the increased dosage of zinc oxide nanoparticle addition in the diesel fuel at low engine speeds (between 1400-2000 rpm). It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power increase according to diesel fuel result is 9.8%, 9.9% and 11.8% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power increase was obtained at 2800 rpm engine speed for the all modified fuels. The maximum brake power reduction according to diesel fuel result is 4.2%, 2.6% and 3.6% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power reduction was obtained at 1800 rpm for 25 ppm, 1200 rpm for 50 ppm and 1400 rpm engine speed for the 100 ppm zinc oxide nanoparticle addition dosage. The average brake power increase is 0.7%, 1% and 1.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average brake power increase values increased with the increased dosage of zinc oxide nanoparticle addition in the diesel fuel.

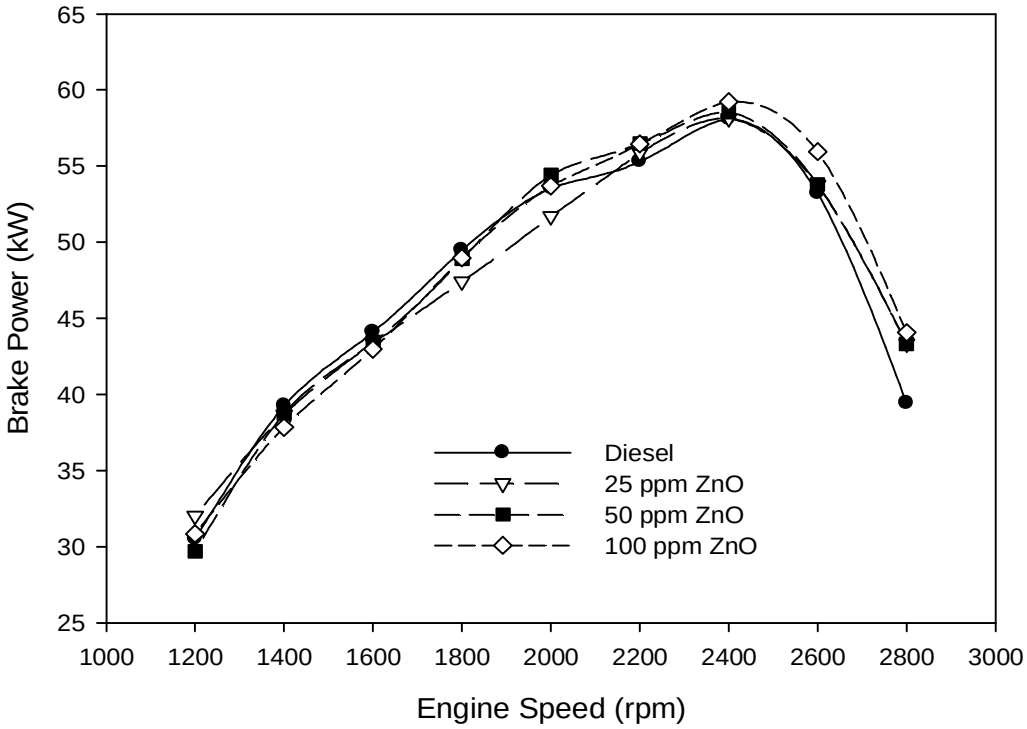


Figure 4.17. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.18. Generally torque output values increased with the increased dosage of zinc oxide nanoparticle addition in the diesel fuel at high engine speeds (between 2600 and 2800 rpm) and decreased with the increased dosage of zinc oxide nanoparticle addition in the diesel fuel at low engine speeds (between 1200-2400 rpm). The maximum torque values for all fuels were obtained at an engine speed of 1400-1600 rpm. The maximum torque output reduction according to diesel fuel result is 1.3%, 1.6% and 2.2% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque reduction was obtained at 1200 rpm engine speed for the all modified fuels. The maximum torque output increase according to diesel fuel result is 5.2%, 5.4% and 7.4% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque increase was achieved at 2800 rpm engine speed for the all modified fuels. There are no significant differences in the torque output values averagely at all engine speeds with the addition of 25, 50 and 100 ppm dosage zinc oxide nanoparticles to the diesel fuel.

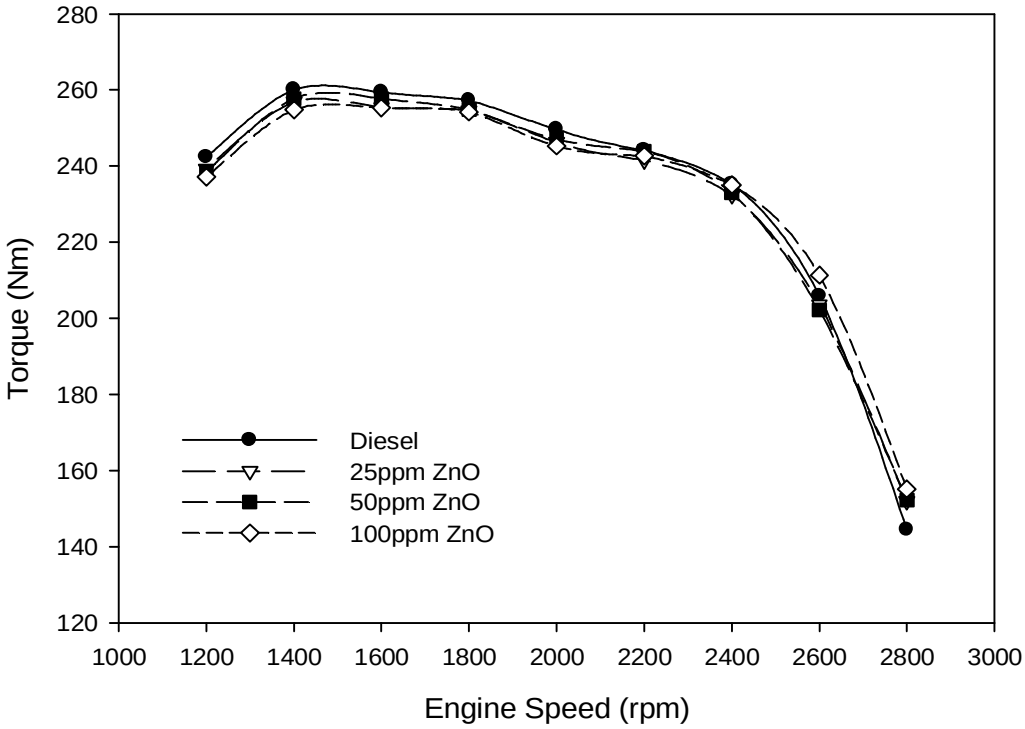


Figure 4.18. Torque output versus engine speed for the test fuels

4.3.3. Exhaust Emissions

Figure 4.19 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. ZnO nanoparticle addition dosage of 50 ppm and 100 ppm decreased the CO emissions and addition dosage of 25 ppm increased the CO emissions values with respect to diesel fuel. The maximum CO emission reduction according to diesel fuel result is 11.9%, 17.8% for the modified fuels at the nanoparticle addition dosage of 50, 100 ppm respectively. The maximum CO emission reduction was obtained at 2200 rpm engine speed. The maximum CO emission increase according to diesel fuel result is 17.5% for the modified fuel at the nanoparticle addition dosage of 25 ppm. The maximum CO emission increase was obtained at 2800 rpm engine speed. The average reduction is 3.2% and 9% according to base fuel (diesel fuel) at the ZnO nanoparticle addition dosage of 50, 100 ppm respectively. The average increase is 6.2% according to base fuel at the addition dosage of 25 ppm.

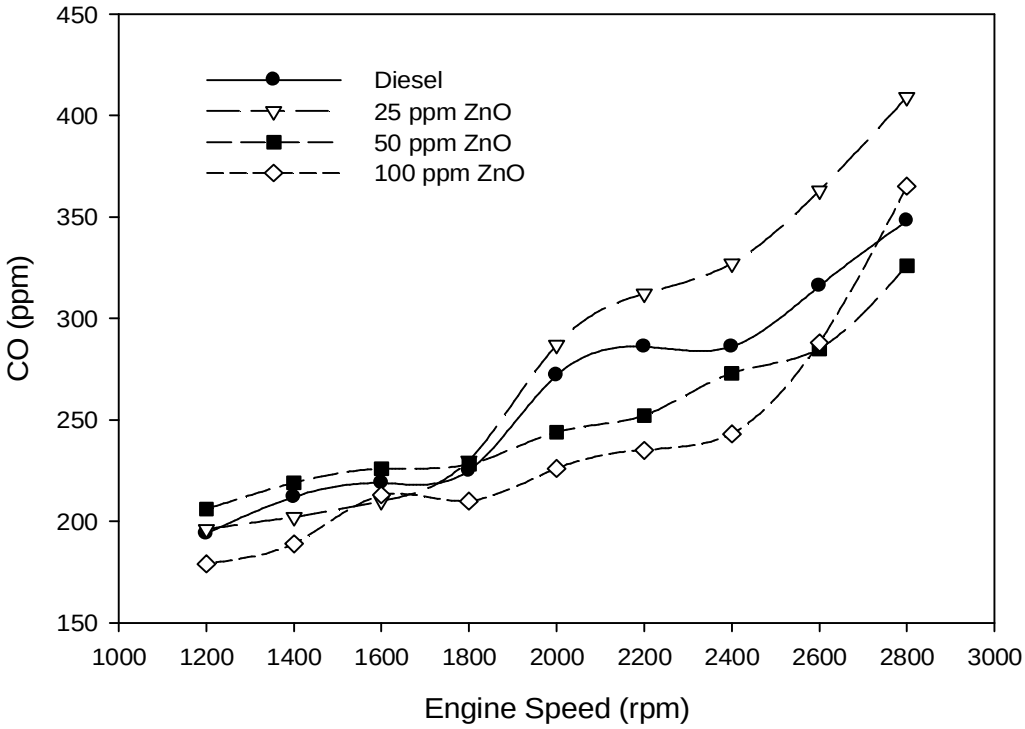


Figure 4.19. CO emission values of test fuels

Figure 4.20 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. ZnO nanoparticle addition dosage of 25, 50 and 100 ppm increased the CO_2 emissions values of the diesel fuel. The maximum CO_2 emission increase according to diesel fuel result is 12.3%, 10.8% and 12.5% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO_2 emission increase was obtained at 1400 rpm engine speed for 25 ppm addition and at 2600 rpm engine speed for the 50 and 100 ppm addition dosage. The average increment is 1.1%, 4.4% and 6.3% according to base fuel (diesel fuel) at the ZnO nanoparticle addition dosage of 25, 50 and 100 ppm respectively. Average CO_2 increment values increased with the increased dosage of zinc oxide nanoparticle addition in the diesel fuel.

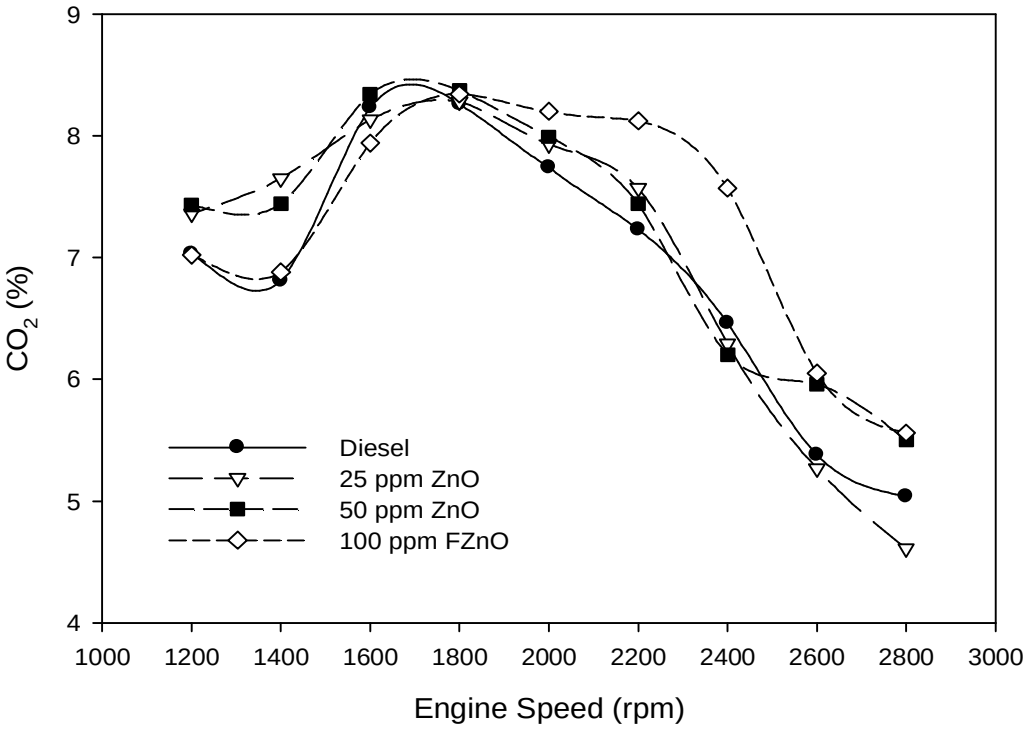


Figure 4.20. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.21. The maximum NO_x emissions were measured with modified fuel with the ZnO addition dosage of 100 ppm. ZnO nanoparticle addition dosage of 25 ppm and 50 ppm decreased the NO_x emissions and addition dosage of 100 ppm increased the NO_x emissions values with respect to diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 14.2% and 5.6% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 2800 rpm engine speed for 25 ppm addition and at 1800 rpm for 50 ppm addition dosage. The maximum increase is 12% and was obtained at 2600 rpm engine speed with the 100 ppm ZnO nanoparticle addition dosage. The average reduction is 3.2% and 1% according to base fuel (diesel fuel) at the addition dosage of 25 and 50 ppm respectively. The average increase is 2.1% according to base fuel at the addition dosage of 100 ppm.

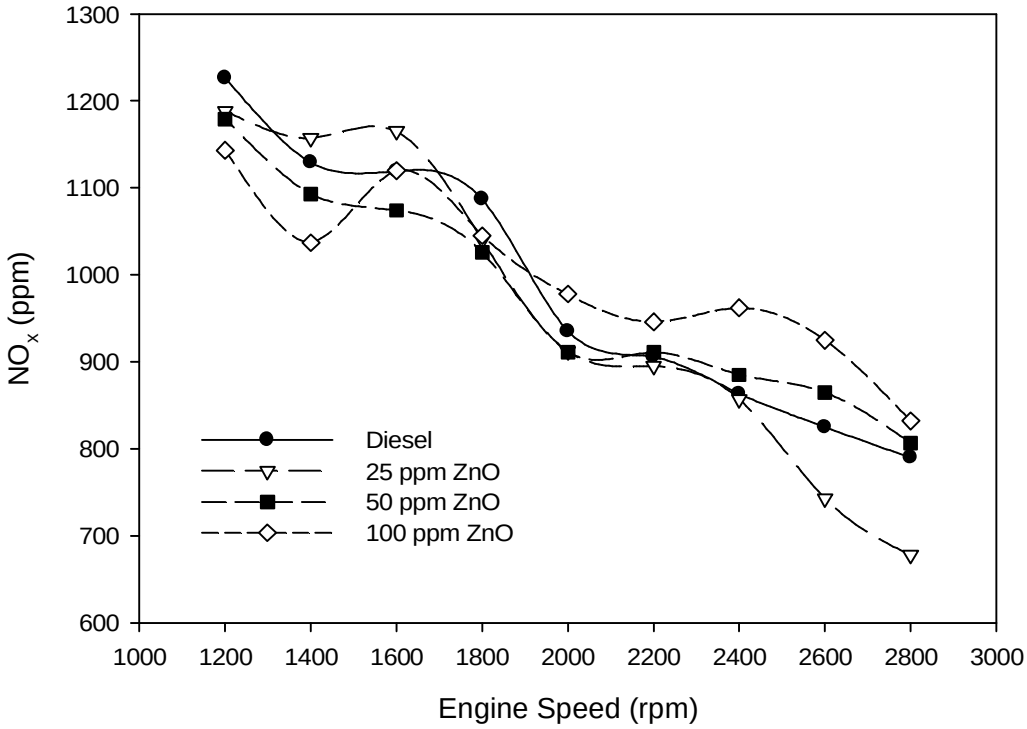


Figure 4.21. NO_x emission values of test fuels

4.5. Effects of Iron Oxide (Fe_2O_3) Nanoparticle Additive on Diesel Fuel

4.5.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of diesel and modified diesel fuels were given in Table 4.5. Also European petrodiesel standard EN 590 was given in Table 4.5.

Table 4.5. Fuel Properties of Diesel and Modified Diesel Fuels

Property	**Units**	**EN 590**	**Diesel**	**25 ppm Fe_2O_3**	**50 ppm Fe_2O_3**	**100 ppm Fe_2O_3**
Density at 15°C	kg/m³	820-845	833	833	833	833
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	2.88	2.90	3.03
Flash point	°C	Min 55	58.5	62.5	65.5	66.5
Cetane number	-	Min 51	56	47.6	47.3	41.4
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) Fe_2O_3 nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was slightly increased with the addition of Fe_2O_3 nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.88 mm^2/s, 2.90 mm^2/s and 3.03 mm^2/s at the dosage of 25, 50 and 100 ppm Fe_2O_3 nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the Fe_2O_3 nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 62.5 °C, 65.5 °C and 66.5 °C respectively. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm iron oxide nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of Fe_2O_3 nanoparticle. It was decreased to 47.6, 47.3 and 41.4 at the dosage of 25, 50 and 100 ppm Fe_2O_3 nanoparticles addition respectively. Cetane number of the modified fuels with the Fe_2O_3 nanoparticle addition dosage of 25, 50 and 100 ppm are outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm iron oxide nanoparticles to diesel fuel, as shown in Table 4.5 abstracting the measurement of these properties.

4.5.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.22. Generally power output values decreased with iron oxide nanoparticle addition in the diesel fuel at high engine speeds (between 1800 and 2800 rpm) and increased with iron oxide nanoparticle addition in the diesel fuel at low engine speeds (between 1200-1600 rpm). It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power increase according to diesel fuel result is 6.4%, 4% and 4.1% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power increase was obtained at 1400 and 1600 rpm engine speeds for the all modified fuels. The maximum brake power reduction according to diesel fuel result is 5.6%, 6.3% and 6.6% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power reduction was obtained at 1800 rpm for 25 ppm and 2000 rpm engine speed for the 50 and 100 ppm iron oxide nanoparticle addition dosage. The average brake power reduction is 1.5%, 3.9% and 0.6% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

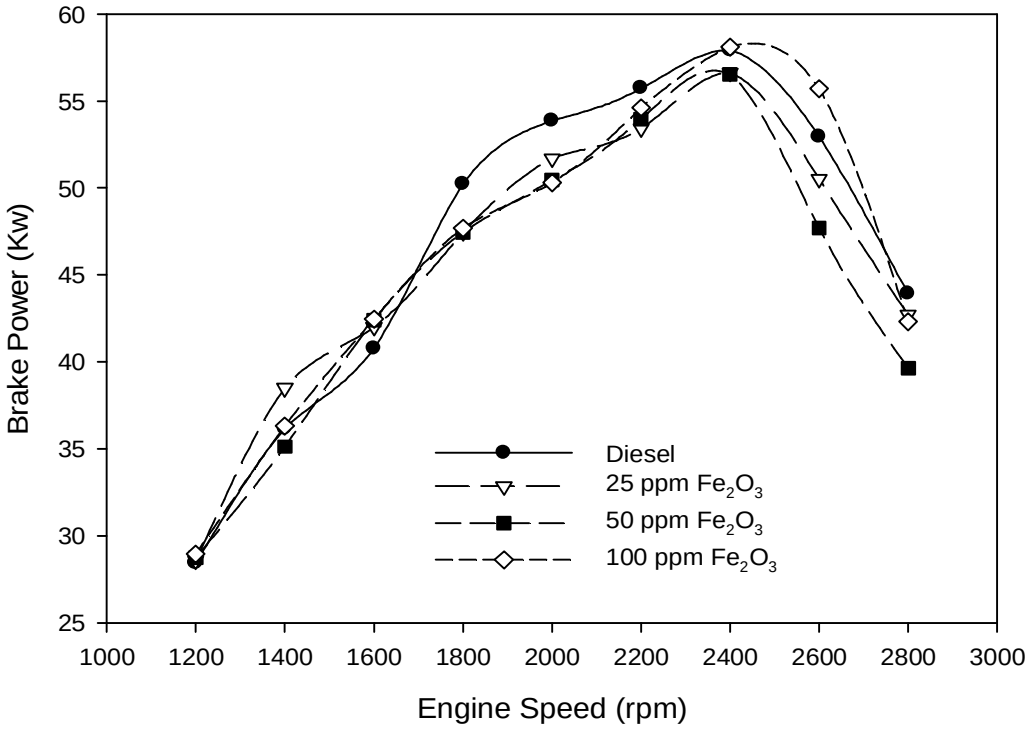


Figure 4.22. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.23. Generally torque output values decreased with iron oxide nanoparticle addition in the diesel fuel at high engine speeds (between 1800 and 2800 rpm) and increased with iron oxide nanoparticle addition in the diesel fuel at low engine speeds (between 1200-1600 rpm). The maximum torque values for the modified fuels obtained at engine speeds of 1400-1600 rpm and for diesel fuel it was obtained at 2000 rpm engine speed. The maximum torque output reduction according to diesel fuel result is 7.4%, 14.2% and 6% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque reduction was obtained at 2600 rpm engine speed for the all modified fuels. The maximum torque output increase according to diesel fuel result is 4.1%, 2.4% and 3.44% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque increase was achieved at 1400 rpm engine speed for the all modified fuels. The average torque output reduction is 1.7%, 3.4% and 1% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

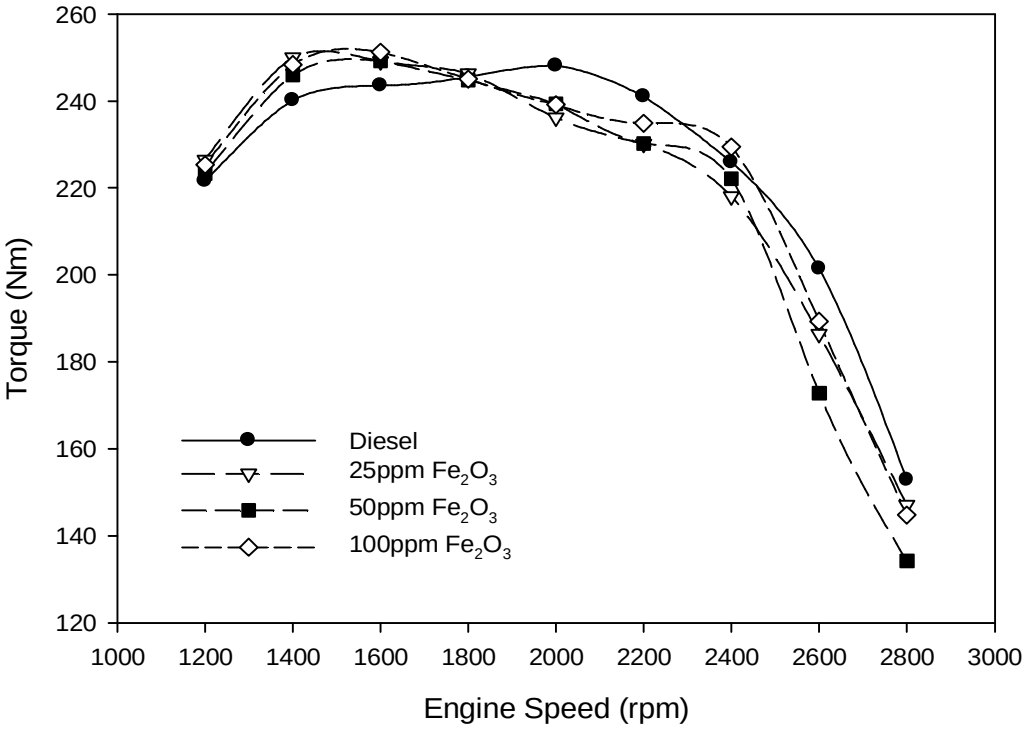


Figure 4.23. Torque output versus engine speed for the test fuels

4.5.3. Exhaust Emissions

Figure 4.24 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. Generally Fe_2O_3 nanoparticle addition to diesel fuel decreased the CO emissions values. Nanoparticle addition increased the CO emissions at low engine speeds of 1200 and 1400 rpm. The maximum CO emission reduction according to diesel fuel result is 16.1%, 10.4% and 10.9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The average reduction is 3.5%, 2.8% and 0.7% according to base fuel (diesel fuel) at the Fe_2O_3 nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

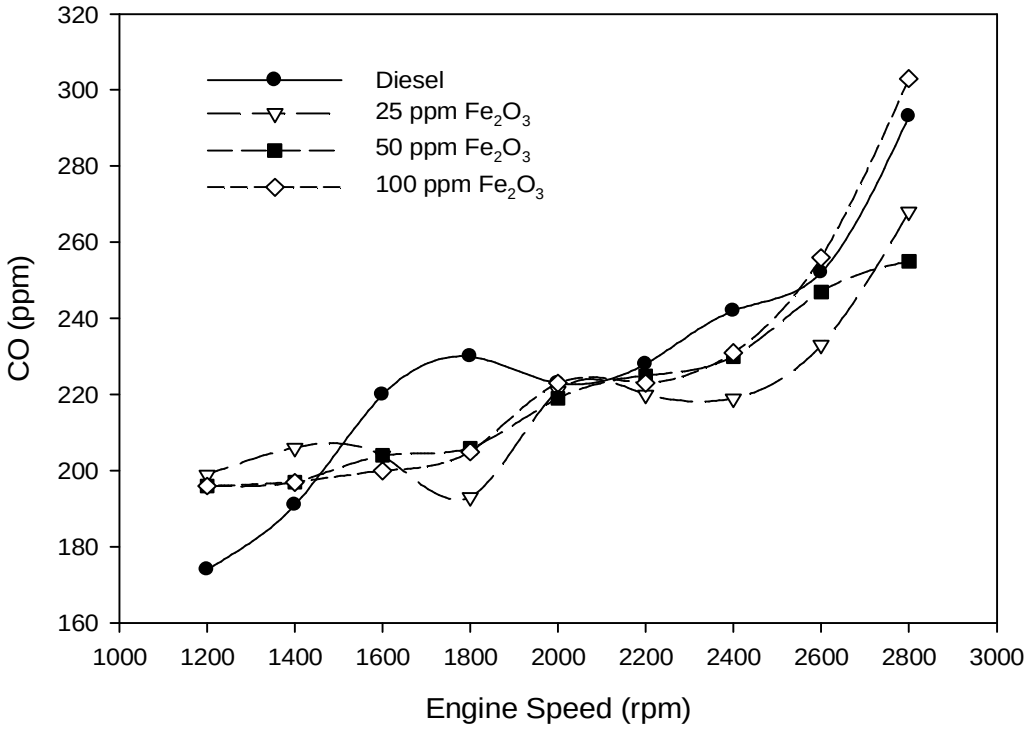


Figure 4.24. CO emission values of test fuels

Figure 4.25 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. Fe_2O_3 nanoparticle addition dosage of 25, 50 and 100 ppm decreased the CO_2 emissions values of the diesel fuel. The average reduction is 0.6%, 2.9% and 0.2% according to base fuel (diesel fuel) at the Fe_2O_3 nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

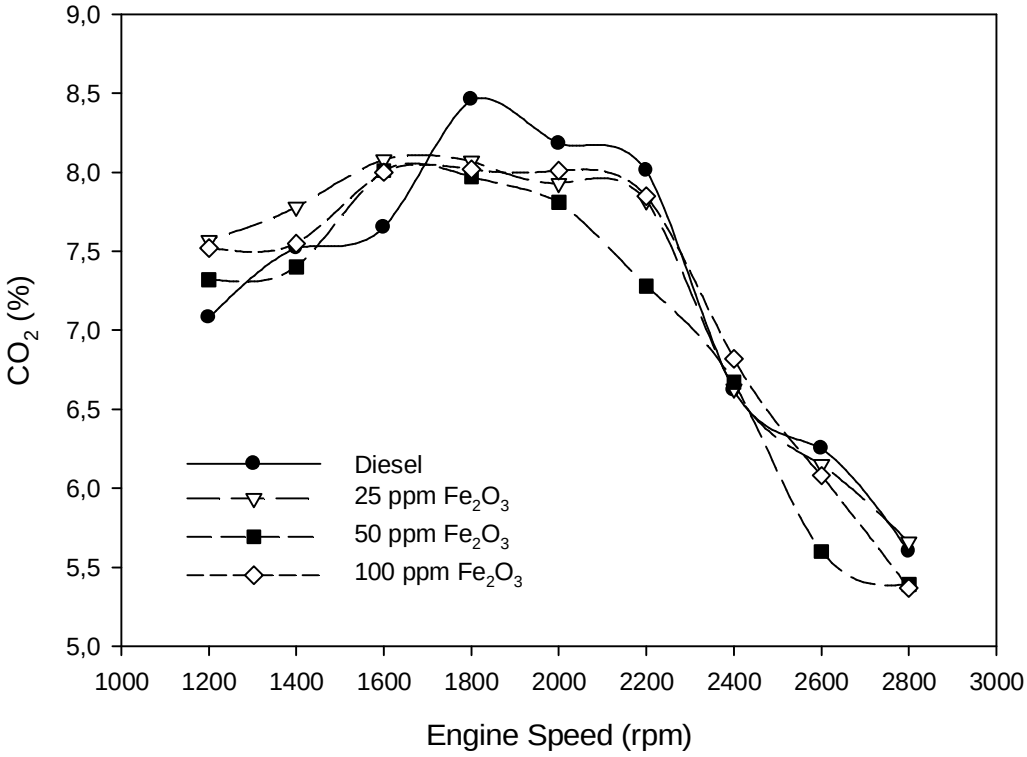


Figure 4.25. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.26. The maximum NO_x emissions were measured with the base fuel (diesel fuel). Fe_2O_3 nanoparticle addition dosage of 25, 50 and 100 ppm decreased the NO_x emissions values of the diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 12.7%, 14.5% and 18.9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 1200 rpm engine speed for 25 ppm addition and at 2800 rpm for 50 and 100 ppm addition dosage. The average reduction is 7.24%, 9.6% and 10.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. The increase in the dosage of the addition was caused to increase in the average reduction of nitrogen oxides emissions values of the diesel fuel.

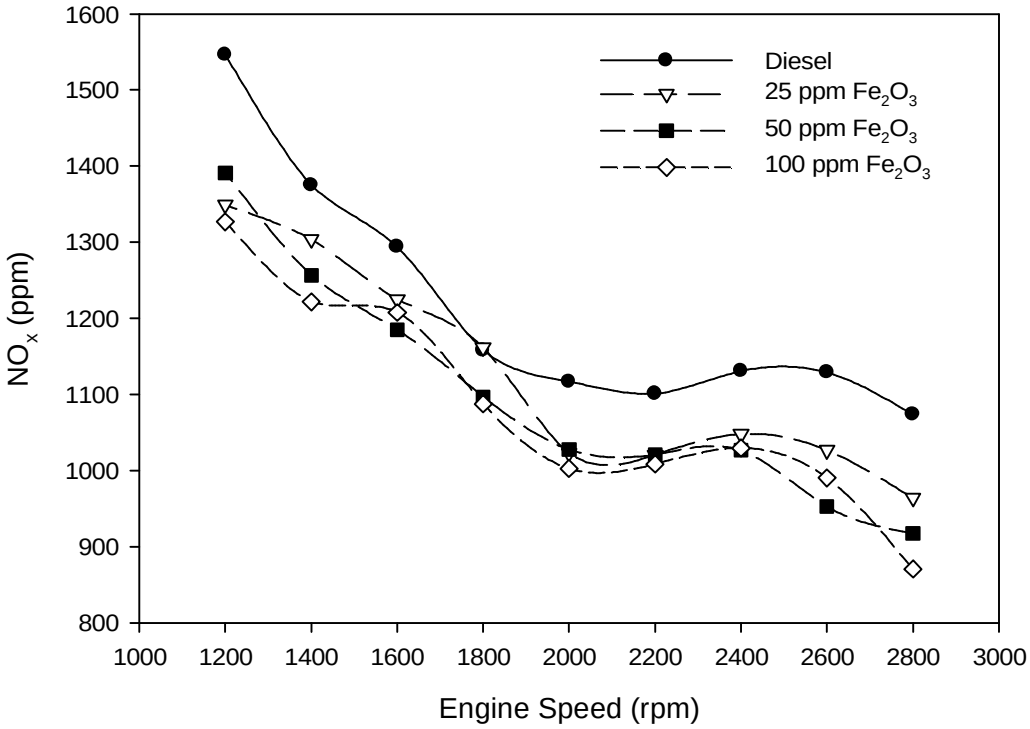


Figure 4.26. NO_x emission values of test fuels

4.6. Effects of Titanium Oxide (TiO_2) Nanoparticle Additive on Diesel Fuel

4.6.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of diesel and modified diesel fuels were given in Table 4.6. Also European petrodiesel standard EN 590 was given in Table 4.6.

Table 4.6. Fuel Properties of Diesel and Modified Diesel Fuels

Property	**Units**	**EN 590**	**Diesel**	**25 ppm TiO_2**	**50 ppm TiO_2**	**100 ppm TiO_2**
Density at 15°C	kg/m³	820-845	833	833	834	833
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	2.85	2.86	2.88
Flash point	°C	Min 55	58.5	58.5	60.7	65.5
Cetane number	-	Min 51	56	40.9	38	36.4
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) TiO_2 nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was not changed considerably with the addition of TiO_2 nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.85 mm^2/s, 2.86 mm^2/s and 2.88 mm^2/s at the dosage of 25, 50 and 100 ppm TiO_2 nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the TiO_2 nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 58.5 °C, 60.7 °C and 65.5 °C respectively. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm titanium oxide nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of TiO_2 nanoparticle. It was decreased to 40.9, 38 and 36.4 at the dosage of 25, 50 and 100 ppm TiO_2 nanoparticles addition respectively. Cetane numbers of the modified fuels with the TiO_2 nanoparticle addition dosage of 25, 50 and 100 ppm are outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm titanium oxide nanoparticles to diesel fuel, as shown in Table 4.6 abstracting the measurement of these properties.

4.6.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.27. Power output values decreased with the increased dosage of titanium oxide nanoparticle addition in the diesel fuel at all engine speeds. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power reduction according to diesel fuel result is 8.2%, 8.3% and 7.6% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power increase was obtained at 1600 rpm engine speed for the 25 and 50 ppm addition and at 1800 rpm engine speed for the 100 ppm addition dosage of titanium oxide nanoparticle. The average brake power reduction is 3%, 4% and 4.3% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average brake power reduction values increased with the increased dosage of titanium oxide nanoparticle addition in the diesel fuel.

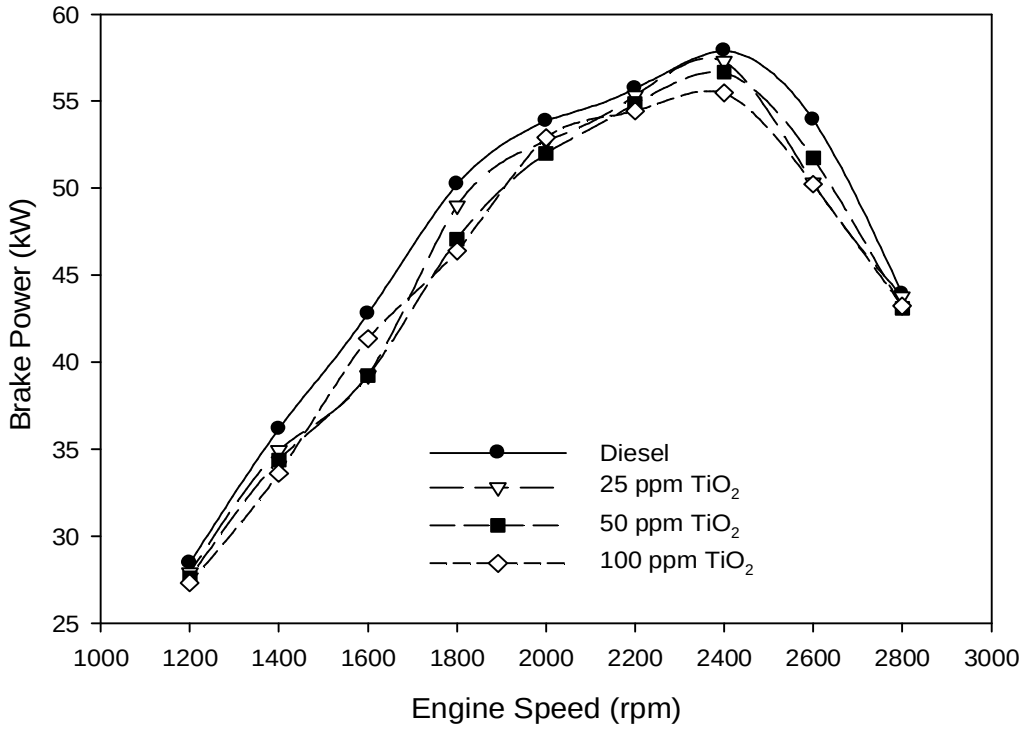


Figure 4.27. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.28. Torque output values decreased with the titanium oxide nanoparticle addition in the diesel fuel at all engine speeds. The maximum torque values for all fuels were obtained at an engine speed of 1800 rpm. The maximum torque output reduction according to diesel fuel result is 7.8%, 3.1% and 3.2% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque reduction was obtained at 2600 rpm engine speed for the 25 and 50 ppm addition dosage and at 2000 rpm engine speed for the 100 ppm titanium oxide nanoparticle addition. The average torque output reduction is 2.3%, 1.9% and 1.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

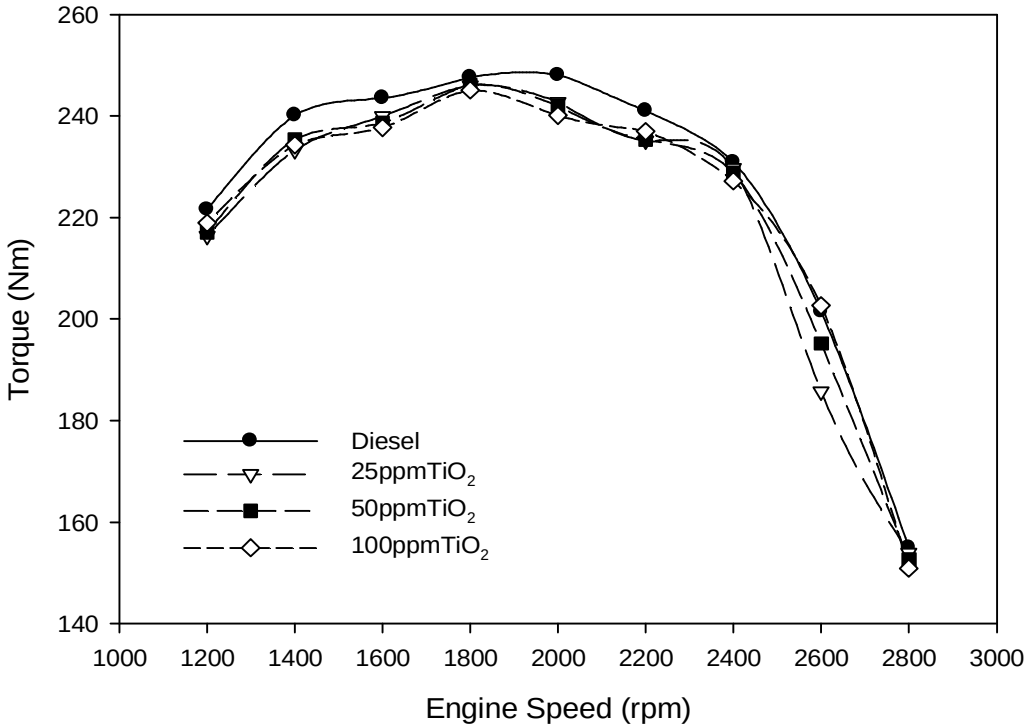


Figure 4.28. Torque output versus engine speed for the test fuels

4.6.3. Exhaust Emissions

Figure 4.29 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. TiO_2 nanoparticle addition dosage of 50

ppm and 100 ppm decreased the CO emissions and addition dosage of 25 ppm increased the CO emissions values with respect to diesel fuel. The maximum CO emission reduction according to diesel fuel result is 17.4% and 13.6% for the modified fuels at the nanoparticle addition dosage of 50 and 100 ppm respectively. The maximum CO emission reduction was obtained at 1600 and 1800 rpm engine speeds. The maximum CO emission increase according to diesel fuel result is 19.4% for the modified fuel at the nanoparticle addition dosage of 25 ppm. The maximum CO emission increase was obtained at 2600 rpm engine speed. The average reduction is 4% and 7.4% according to base fuel (diesel fuel) at the TiO_2 nanoparticle addition dosage of 50, 100 ppm respectively. The average increase is 8% according to base fuel at the addition dosage of 25 ppm.

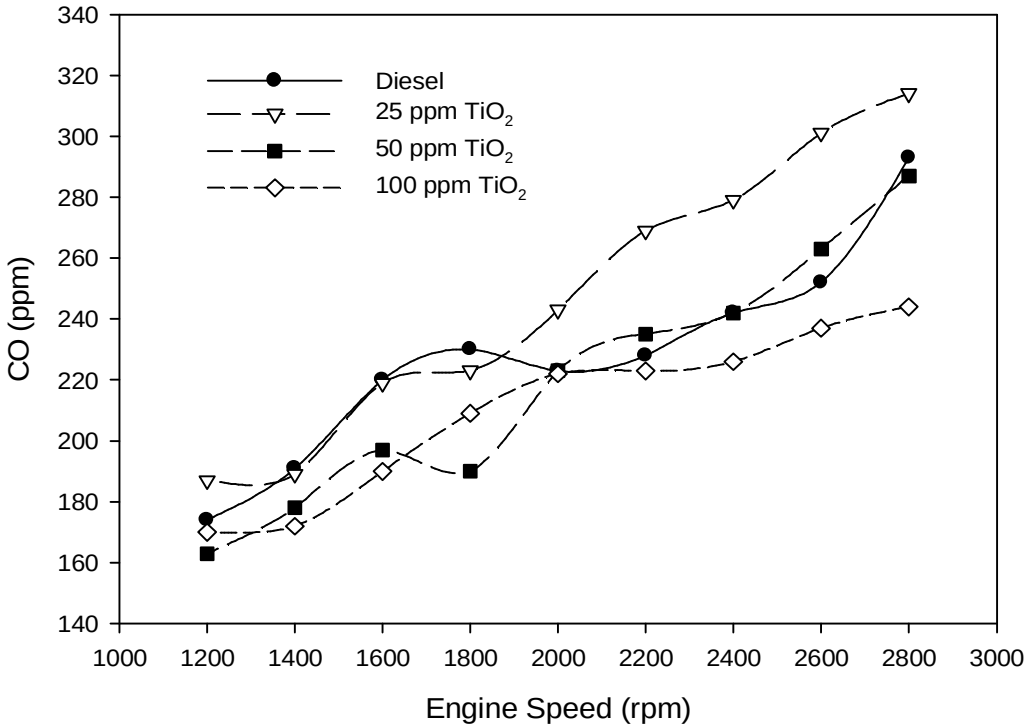


Figure 4.29. CO emission values of test fuels

Figure 4.30 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. TiO_2 nanoparticle addition dosage of 25, 50 and 100 ppm decreased the CO_2 emissions values of the diesel fuel. The maximum CO_2 emission decrease according to diesel fuel result is 10.4%, 13.4% and 14.2% for the modified fuels at

the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO_2 emission decrease was obtained at 1600, 1400 and 1200 rpm engine speeds for the 25, 50 and 100 ppm addition dosage respectively. The average reduction is 6.1%, 9.9% and 7.2% according to base fuel (diesel fuel) at the TiO_2 nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

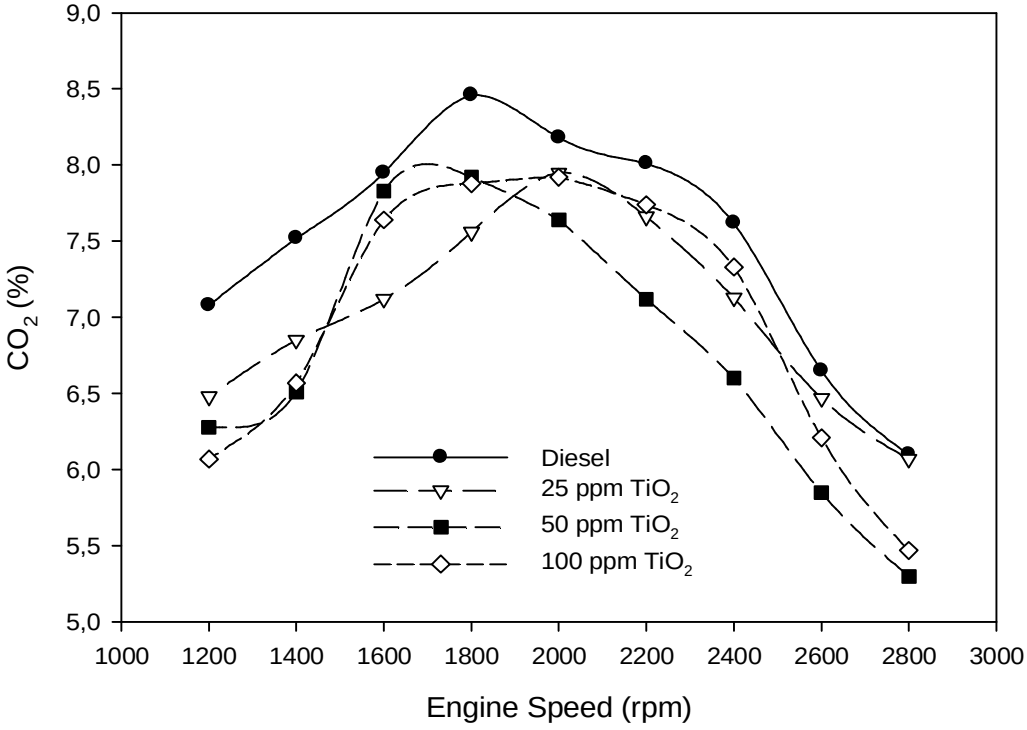


Figure 4.30. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.31. The maximum NO_x emissions were measured with the diesel fuel. TiO_2 nanoparticle addition dosage of 25, 50 and 100 ppm decreased the NO_x emissions with respect to diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 8.8%, 9.7% and 16.2% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 1200, 2800 and 1400 engine speeds for 25, 50 and 100 ppm addition dosage respectively. The average reduction is 10.2%, 6.3% and 6.9% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

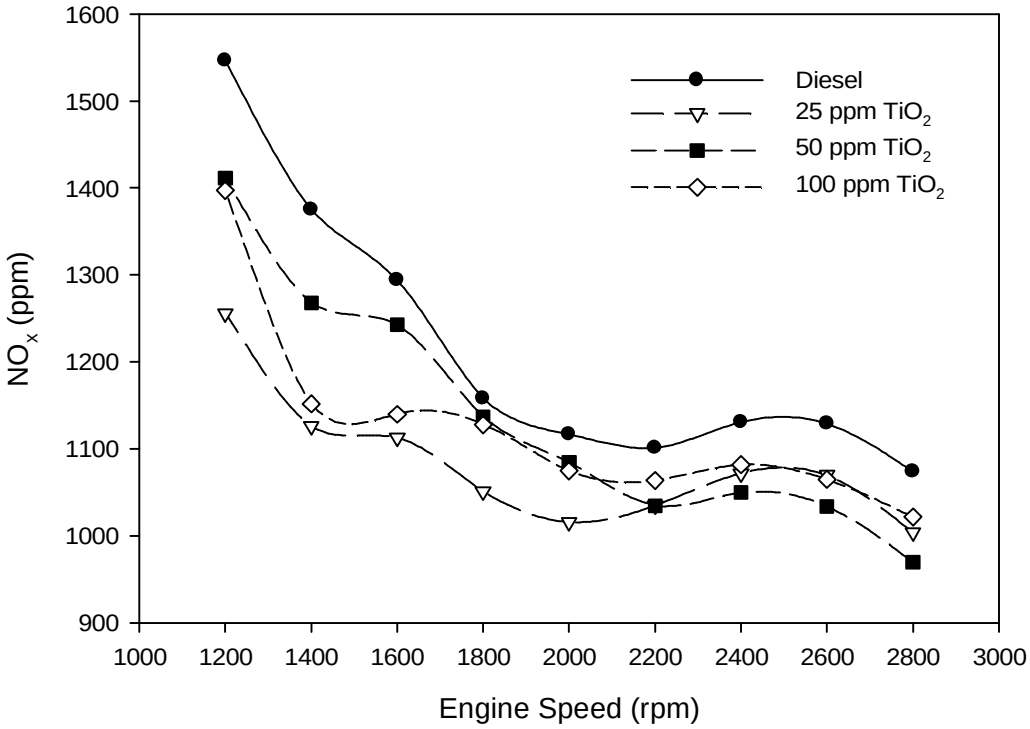


Figure 4.31. NO_x emission values of test fuels

4.7. Effects of Nickel Oxide (NiO) Nanoparticle Additive on Diesel Fuel

4.7.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Obtained fuel properties of diesel and modified diesel fuels were given in Table 4.7. Also European petrodiesel standard EN 590 was given in Table 4.7.

Table 4.7. Fuel Properties of Diesel and Modified Diesel Fuels

Property	Units	EN 590	Diesel	25 ppm NiO	50 ppm NiO	100 ppm NiO
Density at 15°C	kg/m³	820-845	833	834	834	834
Viscosity at 40°C	mm²/s	2.0-4.5	2.85	3.34	3.39	3.49
Flash point	°C	Min 55	58.5	64.5	64.5	64.5
Cetane number	-	Min 51	56	54.5	51.6	45.3
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) NiO nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was increased with the addition of NiO nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 3.34 mm^2/s, 3.39 mm^2/s and 3.49 mm^2/s at the dosage of 25, 50 and 100 ppm NiO nanoparticles additive respectively. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the NiO nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 64.5 °C. The flash point of the fuel gives an indication of the volatility of a fuel. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm nickel oxide nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of NiO nanoparticle. It was decreased to 54.5, 51.6 and 45.3 at the dosage of 25, 50 and 100 ppm NiO nanoparticles addition respectively. Cetane number of the modified fuels with the NiO nanoparticle addition dosage of 25 and 50 ppm is in the limits and 100 ppm is outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm nickel oxide nanoparticles to diesel fuel, as shown in Table 4.7 abstracting the measurement of these properties.

4.7.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.32. Power output values decreased with the increased dosage of nickel oxide nanoparticle addition in the diesel fuel at all engine speeds. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power reduction according to diesel fuel result is 4.3%, 4.3% and 6.3% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum brake power increase was obtained at 2800 rpm engine speed for the 25 ppm addition and at 1600 rpm engine speed for the 50 and at 1200 rpm engine speed for the 100 ppm addition dosage of nickel oxide nanoparticle. The average brake power reduction is 2.6%, 3.0% and 3.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average brake power reduction values increased with the increased dosage of nickel oxide nanoparticle addition in the diesel fuel.

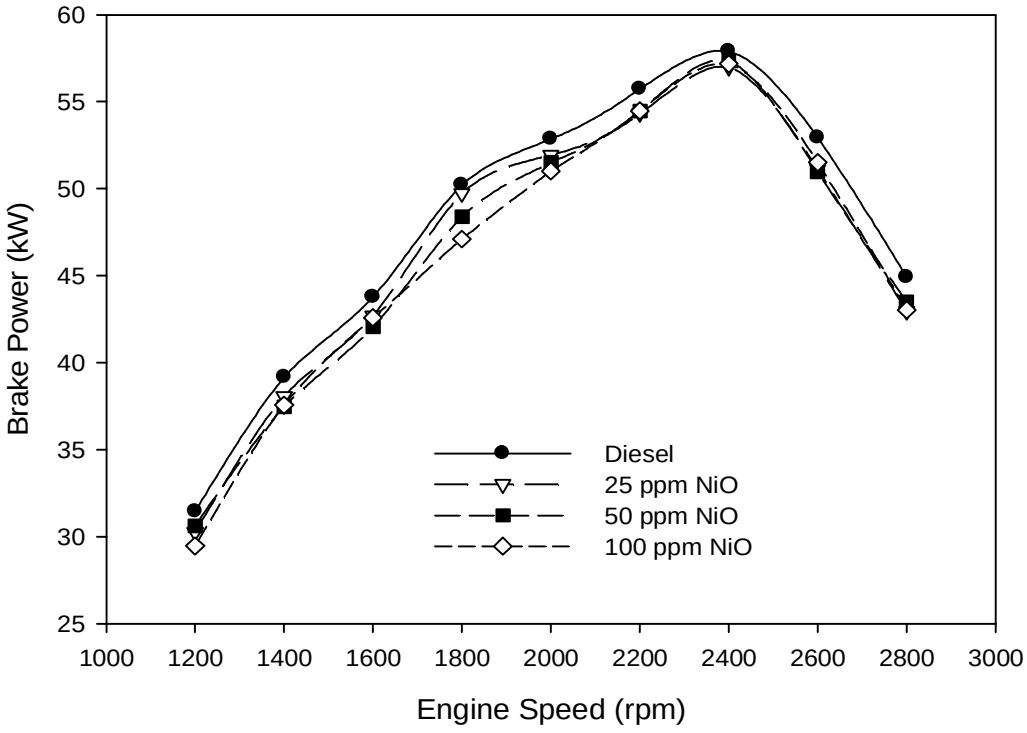


Figure 4.32. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.33. Torque output values decreased with the nickel oxide nanoparticle addition in the diesel fuel at all engine speeds. The maximum torque values for all fuels were obtained at an engine speed of 1600 rpm. The maximum torque output reduction according to diesel fuel result is 2.1%, 2.2% and 2.9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque reduction was obtained at 2600 rpm engine speed for the 25 ppm addition dosage and at 2800 rpm engine speed for the 50 and 100 ppm nickel oxide nanoparticle addition. The average torque output reduction is 2.6%, 3.0% and 3.7% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

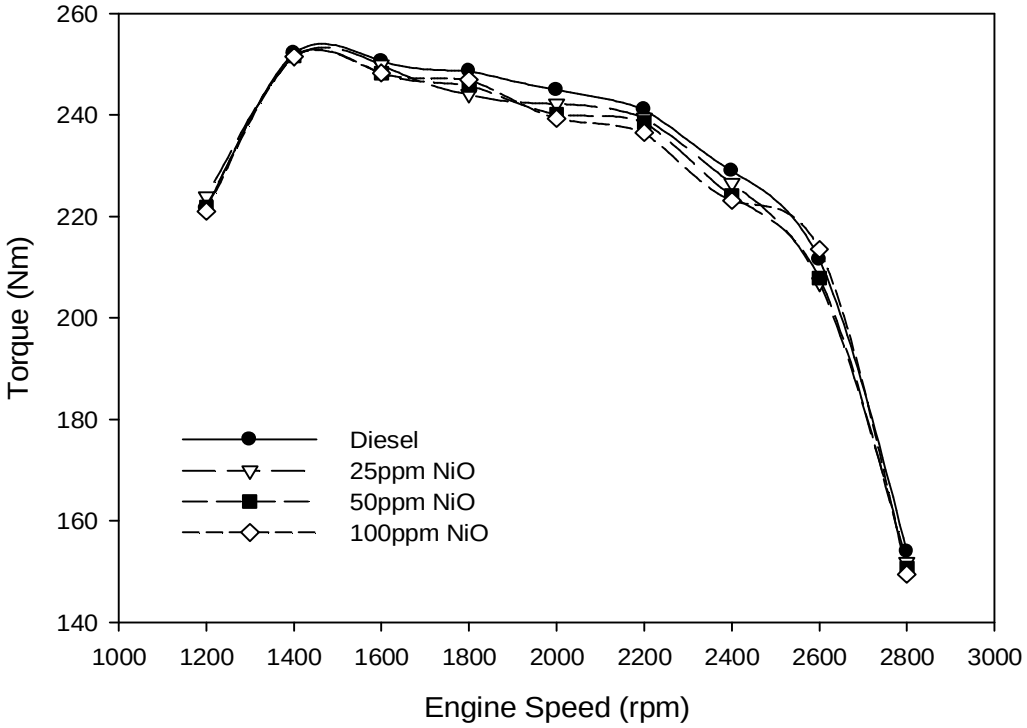


Figure 4.33. Torque output versus engine speed for the test fuels

4.7.3. Exhaust Emissions

Figure 4.34 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. NiO nanoparticle addition dosage of 50 ppm and 100 ppm decreased the CO emissions and addition dosage of 25 ppm

increased the CO emissions values with respect to diesel fuel. The maximum CO emission reduction according to diesel fuel result is 13.5%, 10.4% and 13% for the modified fuels at the nanoparticle addition dosage of 12, 50 and 100 ppm respectively. The maximum CO emission reduction was obtained at 1800 rpm engine speeds. The average reduction is 5%, 8.1% and 9.4% according to base fuel (diesel fuel) at the NiO nanoparticle addition dosage of 25, 50 and 100 ppm respectively. Average CO emission reduction values increased with the increased dosage of nickel oxide nanoparticle addition in the diesel fuel.

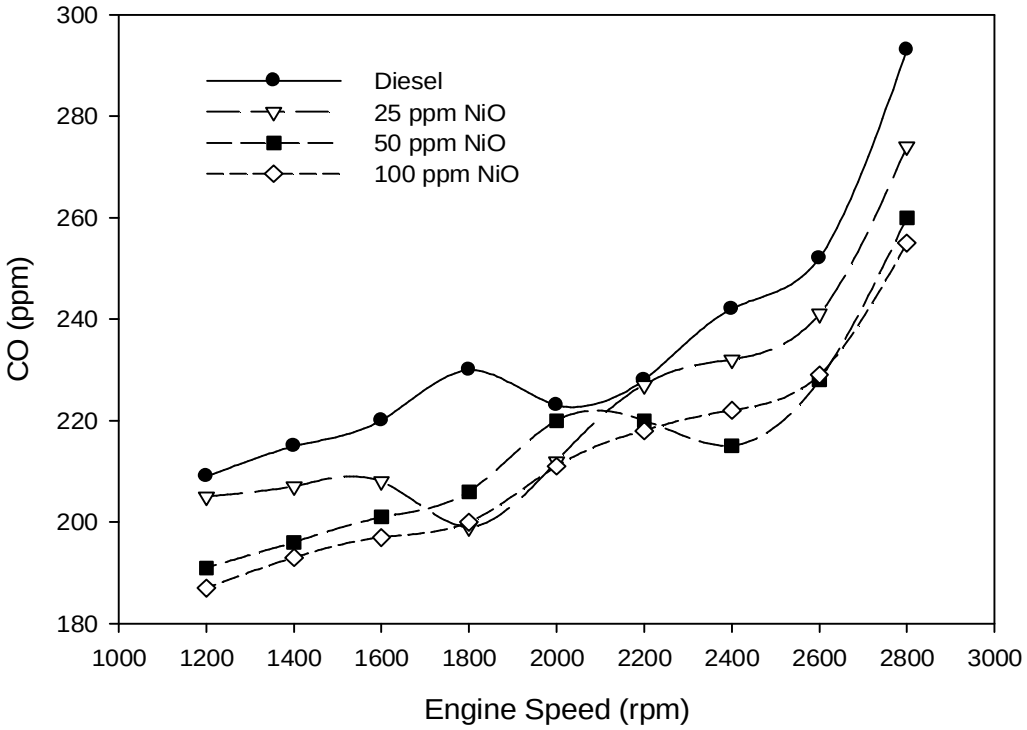


Figure 4.34. CO emission values of test fuels

Figure 4.35 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. NiO nanoparticle addition dosage of 25, 50 and 100 ppm decreased the CO_2 emissions values of the diesel fuel. The maximum CO_2 emission decrease according to diesel fuel result is 9.3%, 3.7% and 4.9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO_2 emission decrease was obtained at 2400 rpm engine speeds for the 25 ppm and at 1200 rpm engine speed for the 50 and 100 ppm addition dosage. The average

reduction is 3.8%, 1.8% and 2.8% according to base fuel (diesel fuel) at the NiO nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

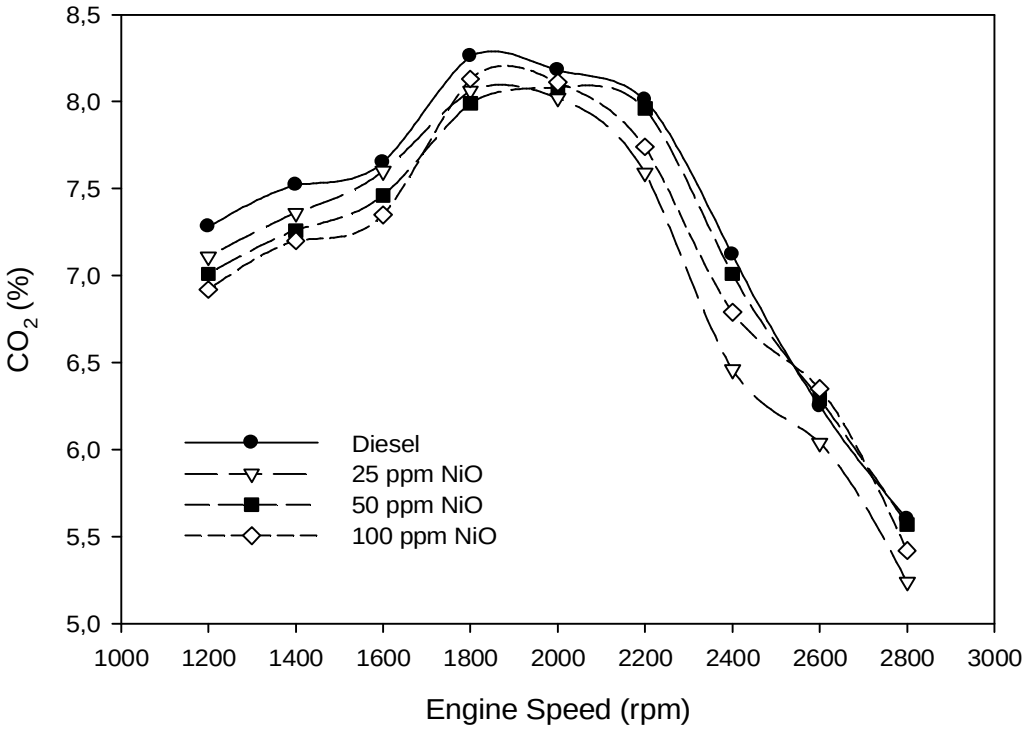


Figure 4.35. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.36. The maximum NO_x emissions were measured with the diesel fuel. NiO nanoparticle addition dosage of 25, 50 and 100 ppm decreased the NO_x emissions with respect to diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 16.4%, 7.9% and 14.3% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 2800, 1400 and 1200 engine speeds for 25, 50 and 100 ppm addition dosage respectively. The average reduction is 8.4%, 4% and 6.5% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

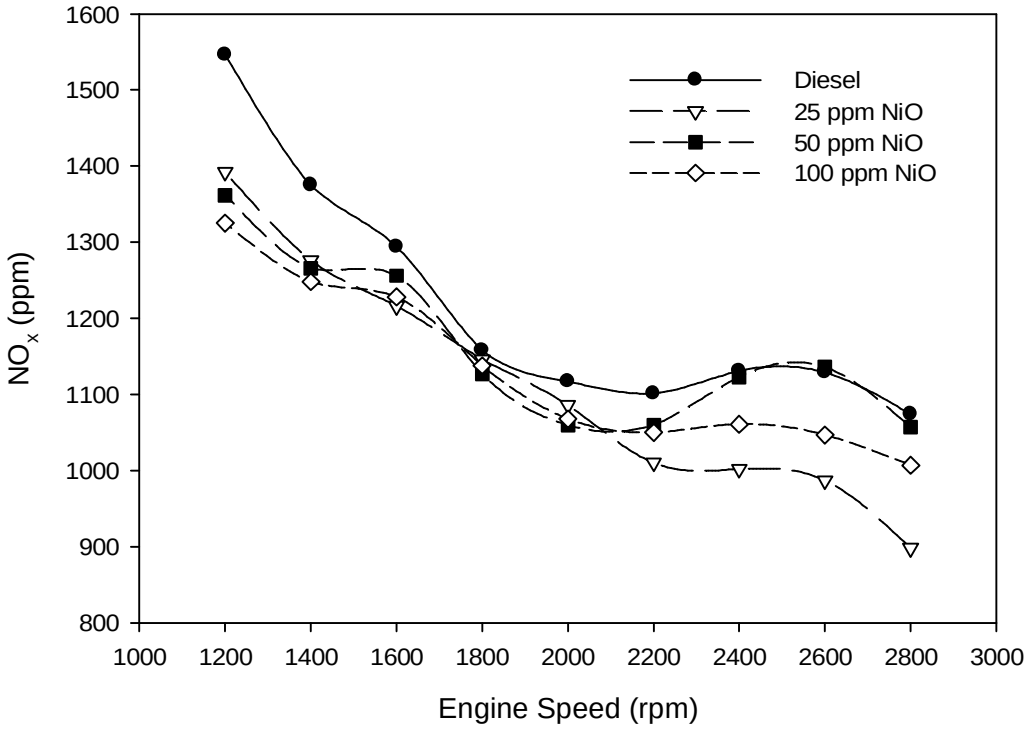


Figure 4.36. NO_x emission values of test fuels

4.8. Effects of Nickel Zinc Iron Oxide ($Zn_{0.5}Ni_{0.5}Fe_2O_4$) Nanoparticle Additive on Diesel Fuel

4.8.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Obtained fuel properties of diesel and modified diesel fuels were given in Table 4.8. Also European petrodiesel standard EN 590 was given in Table 4.8.

Table 4.8. Fuel Properties of Diesel and Modified Diesel Fuels

Property	**Units**	**EN 590**	**Diesel**	**25 ppm $Zn_{0.5}Ni_{0.5}Fe_2O_4$**	**50 ppm $Zn_{0.5}Ni_{0.5}Fe_2O_4$**	**100 ppm $Zn_{0.5}Ni_{0.5}Fe_2O_4$**
Density	kg/m³	820-845	833	834	834	834
Viscosity	mm²/s	2.0-4.5	2.85	2.89	2.95	3.06
Flash point	°C	Min 55	58.5	60.5	62.5	66.5
Cetane number	-	Min 51	56	47.5	46.1	41.6
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was increased with the addition of nickel zinc iron oxide nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.89 mm^2/s, 2.95 mm^2/s and 3.06 mm^2/s at the dosage of 25, 50 and 100 ppm $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticles additive respectively. Viscosity value of the diesel fuel was increased wit the increase in the additive dosage of nickel zinc iron oxide nanoparticles. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 60.5 °C, 62.5 °C and 66.5 °C respectively. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm nickel zinc iron oxide nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of nickel zinc iron oxide nanoparticle. It was decreased to 47.5, 46.1 and 41.6 at the dosage of 25, 50 and 100 ppm nickel zinc iron oxide nanoparticles addition respectively. Cetane number is the ignition quality of a fuel. Cetane number of the all modified fuels is outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm nickel zinc iron oxide nanoparticles to diesel fuel, as shown in Table 4.8 abstracting the measurement of these properties.

4.8.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.37. Power output values in most cases decreased with the addition of nickel zinc iron oxide nanoparticle to diesel fuel. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power reduction according to diesel fuel result is 4.1%, 6.4% and 6.2% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The average brake power reduction is 1.3%, 2.1% and 3.1% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average brake power reduction values increased with the increased dosage of nickel zinc iron oxide nanoparticle addition in the diesel fuel.

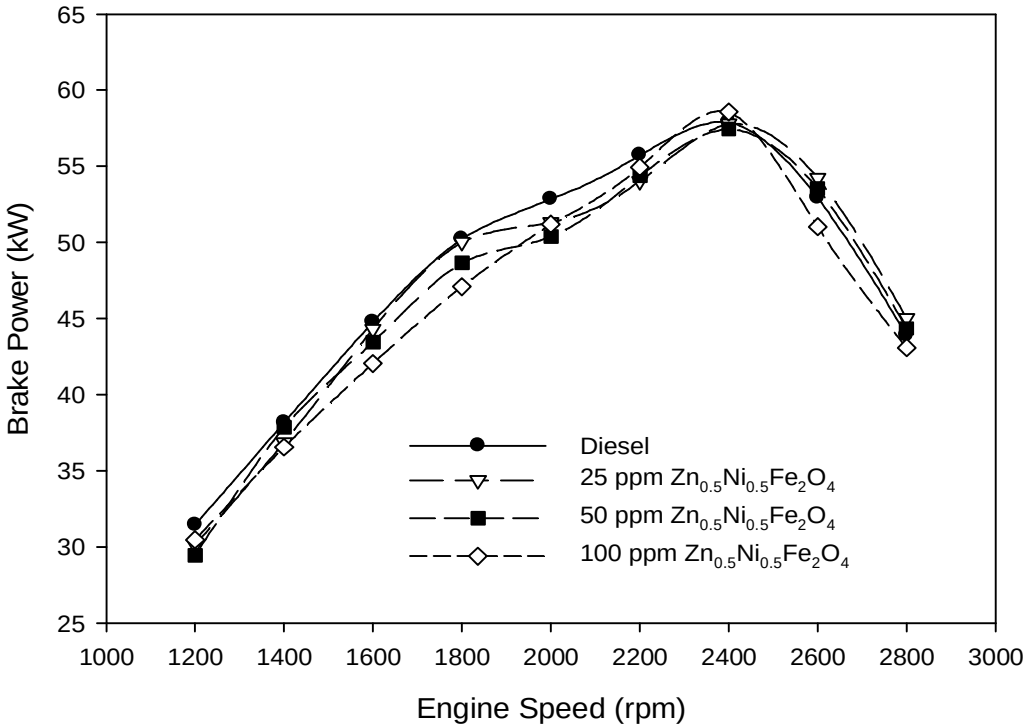


Figure 4.37. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.38. Torque output values commonly decreased with the nickel zinc iron oxide nanoparticle addition in the

diesel. The maximum torque values for all fuels were obtained at an engine speed of 1600 rpm. The maximum torque output reduction according to diesel fuel result is 2.1%, 5.3% and 6.2% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque reduction was obtained at 2600 rpm engine speed for the all modified fuels. The average torque output reduction is 0.4%, 1.7% and 1.3% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

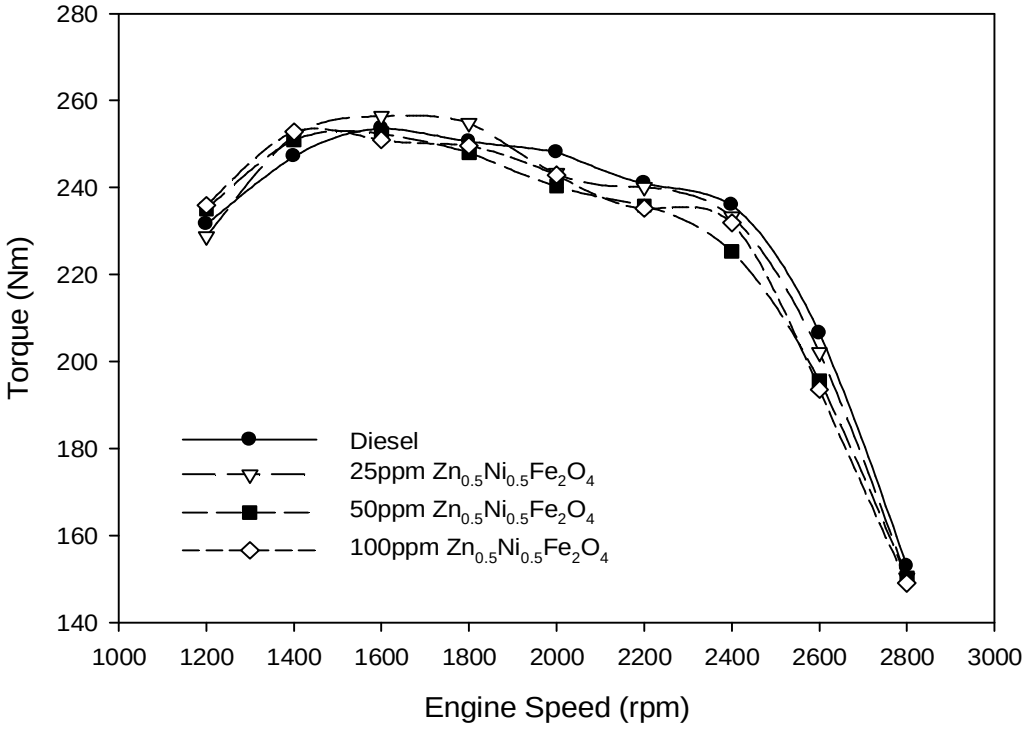


Figure 4.38. Torque output versus engine speed for the test fuels

4.8.3. Exhaust Emissions

Figure 4.39 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm decreased the CO emissions of the diesel fuel. The maximum CO emission reduction according to diesel fuel result is 15%, 14.3% and 10.9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO emission reduction was obtained at 2800 rpm

engine speed for the 25 ppm and at 1800 rpm engine speeds for the 50 and 100 ppm addition dosage. The average reduction is 1.9%, 5.6% and 5.5% according to base fuel (diesel fuel) at the $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

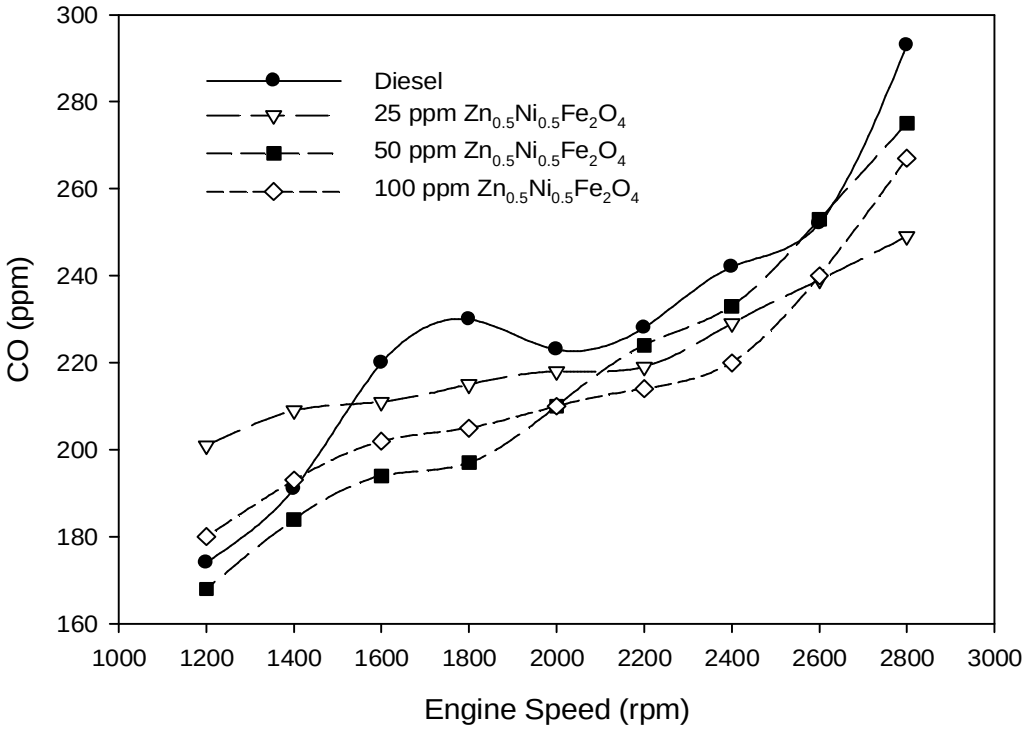


Figure 4.39. CO emission values of test fuels

Figure 4.40 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm decreased the CO_2 emissions values of the diesel fuel. The maximum CO_2 emission reduction according to diesel fuel result is 3.3%, 5.7% and 7.7% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO_2 emission decrease was obtained at 1600 rpm engine speeds for the 25 ppm and at 1400 rpm engine speed for the 50 and 100 ppm addition dosage. The average reduction is 1.4%, 4.9% and 4.4% according to base fuel (diesel fuel) at the $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

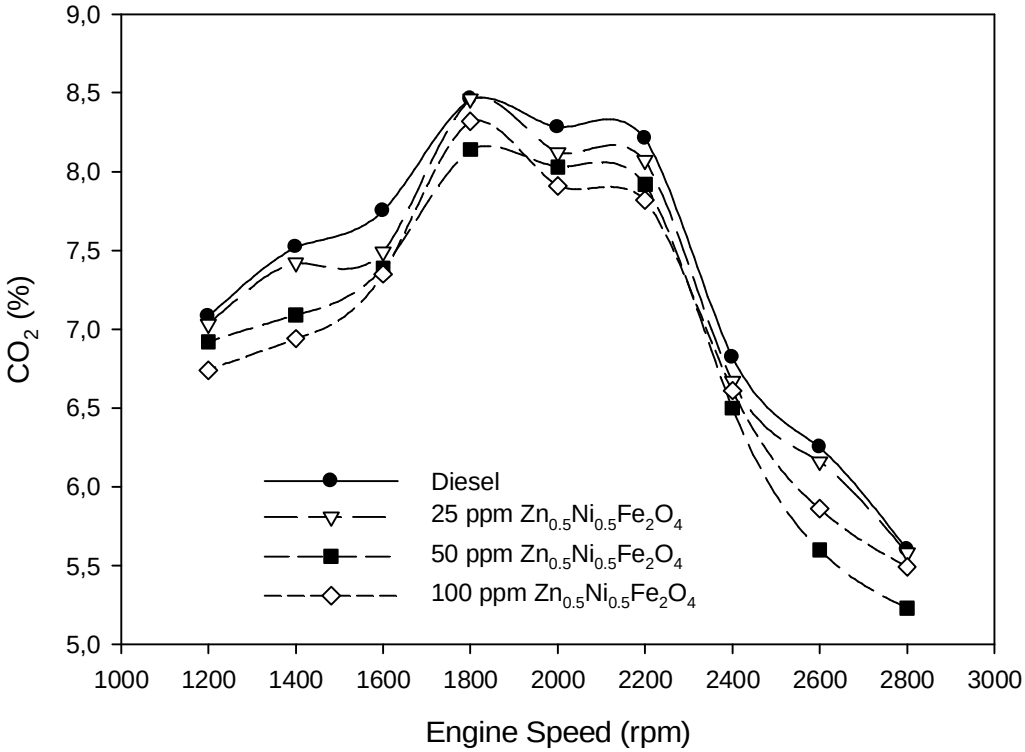


Figure 4.40. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.41. The maximum NO_x emissions were measured with the diesel fuel. $Zn_{0.5}Ni_{0.5}Fe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm decreased the NO_x emissions with respect to diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 15%, 19.3% and 22.5% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 1200 engine speed for the all modified fuels. The average reduction is 5.1%, 9.2% and 12.6% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average nitrogen oxides (NO_x) emission reduction values increased with the increased dosage of nickel zinc iron oxide nanoparticle addition in the diesel fuel.

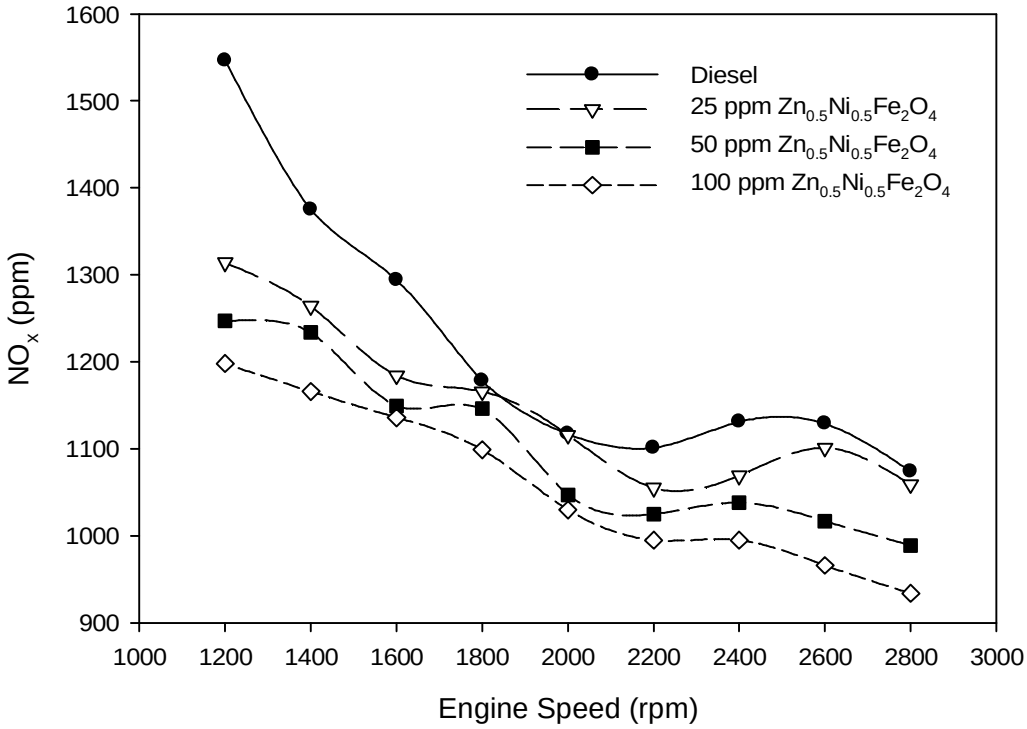


Figure 4.41. NO_x emission values of test fuels

4.9. Effects of Nickel Iron Oxide ($NiFe_2O_4$) Nanoparticle Additive on Diesel Fuel

4.9.1. Fuel Properties

Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of diesel and modified diesel fuels were given in Table 4.9. Also European petrodiesel standard EN 590 was given in Table 4.9.

Table 4.9. Fuel Properties of Diesel and Modified Diesel Fuels

Property	**Units**	**EN 590**	**Diesel**	**25 ppm $NiFe_2O_4$**	**50 ppm $NiFe_2O_4$**	**100 ppm $NiFe_2O_4$**
Density	kg/m³	820-845	833	834	834	833
Viscosity	mm²/s	2.0-4.5	2.85	2.88	2.89	2.92
Flash point	°C	Min 55	58.5	63.5	64.5	64.5
Cetane number	-	Min 51	56	47.2	43.6	38
Pour Point	°C	-	-10	-10	-10	-10

Addition of different dosage of (25, 50 and 100 ppm) $NiFe_2O_4$ nanoparticles has no noticeable effect on density value of diesel fuel.

Kinematic viscosity of diesel fuel was increased with the addition of nickel iron oxide nanoparticles at the dosage of 25, 50 and 100 ppm. Viscosity value of modified fuels is 2.88 mm^2/s, 2.89 mm^2/s and 2.92 mm^2/s at the dosage of 25, 50 and 100 ppm $NiFe_2O_4$ nanoparticles additive respectively. Viscosity value of the diesel fuel was increased wit the increase in the additive dosage of nickel iron oxide nanoparticles. All of the viscosity results are in the acceptable range of EN 590.

Flash point of the diesel fuel was increased with the $NiFe_2O_4$ nanoparticle addition. At the dosage of 25, 50 and 100 ppm it was increased to 63.5 °C, 64.5 °C and 64.5 °C respectively. The flash point result represented that storage and transporting of modified diesel fuels (25, 50 and 100 ppm nickel iron oxide nanoparticles addition to diesel fuel) can be done safely.

Cetane number of the diesel fuel showed decreasing trend with the addition of nickel iron oxide nanoparticle. It was decreased to 47.2, 43.6 and 38 at the dosage of 25, 50 and 100 ppm $NiFe_2O_4$ nanoparticles addition respectively. Cetane number of the all modified fuels is outside the limits of EN 590.

No significant differences were observed in the pour points due to the addition of 25, 50 and 100 ppm nickel iron oxide nanoparticles to diesel fuel, as shown in Table 4.9 abstracting the measurement of these properties.

4.9.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.42. Power output values increased with the addition of nickel iron oxide nanoparticle to diesel fuel. It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power increase according to diesel fuel result is 10.1%, 16.7% and 17.8% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The average brake power increase is 5.5%, 4.8% and 4.0% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average brake power increment values decreased with the increased dosage of nickel iron oxide nanoparticle addition in the diesel fuel.

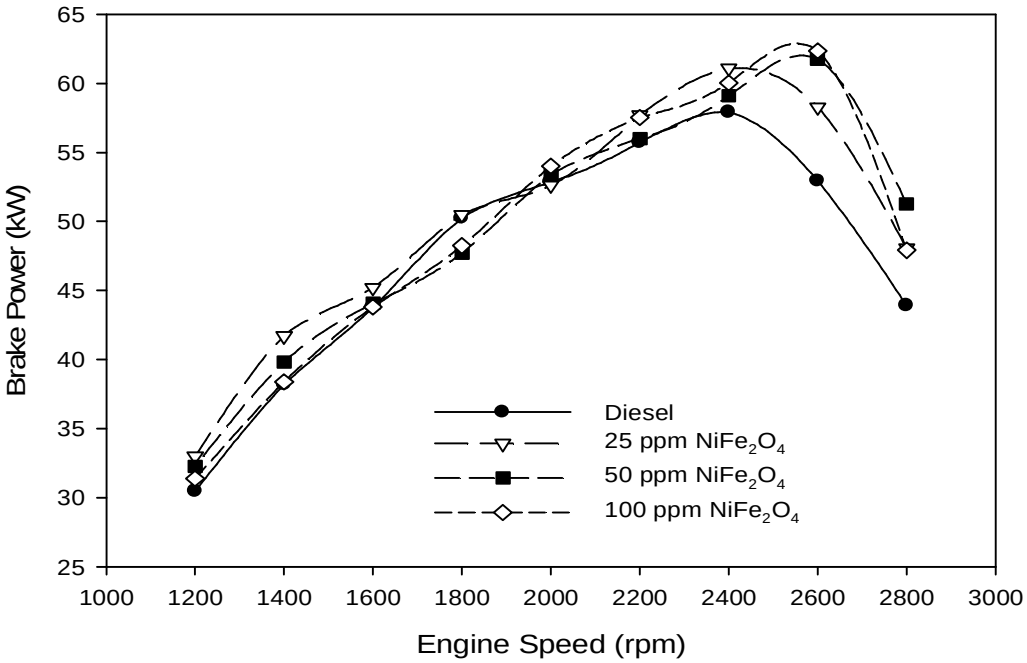


Figure 4.42. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.43. Torque output values commonly increased with the nickel iron oxide nanoparticle addition in the diesel. The maximum torque values for all fuels were obtained at engine speeds of 1400-1600 rpm. The maximum torque output increase according to diesel fuel result is

8.7%, 14.7% and 9% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum torque increase was obtained at 2800 rpm engine speed for the all modified fuels. The average torque output increase is 2.7%, 3.1% and 2.6% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively.

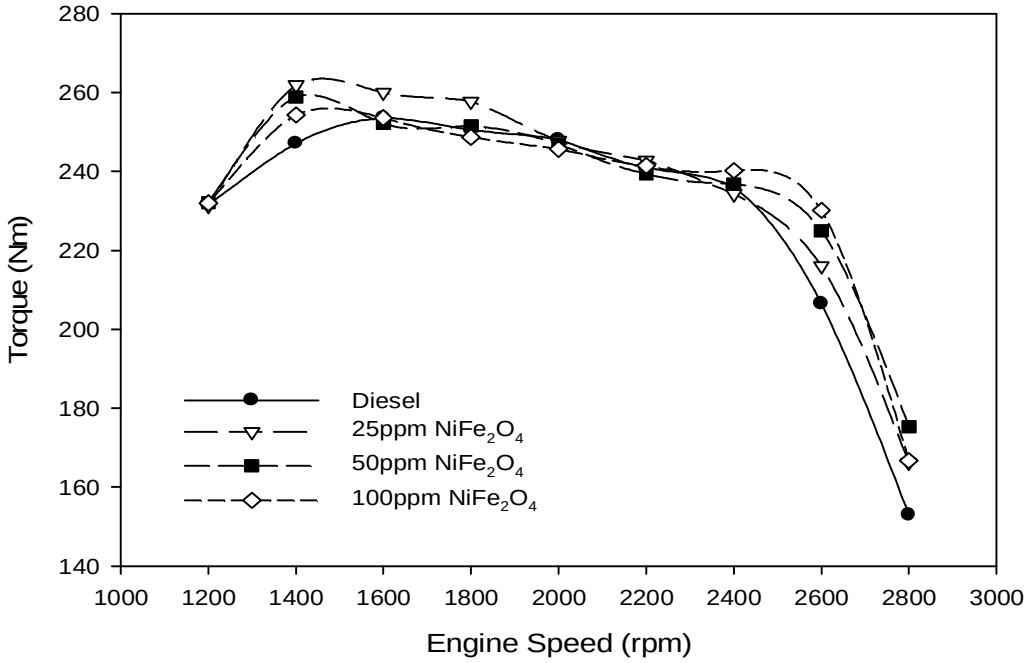


Figure 4.43. Torque output versus engine speed for the test fuels

4.9.3. Exhaust Emissions

Figure 4.44 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. $NiFe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm decreased the CO emissions of the diesel fuel. The maximum CO emission reduction according to diesel fuel result is 15.7%, 23.5% and 6.8% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO emission reduction was obtained at 2800 rpm engine speed for the 25 and 50 ppm and at 1600 rpm engine speeds for the 100 ppm addition dosage. The average reduction is 1.9%, 4.9% and 1.4% according to base fuel (diesel

fuel) at the $NiFe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

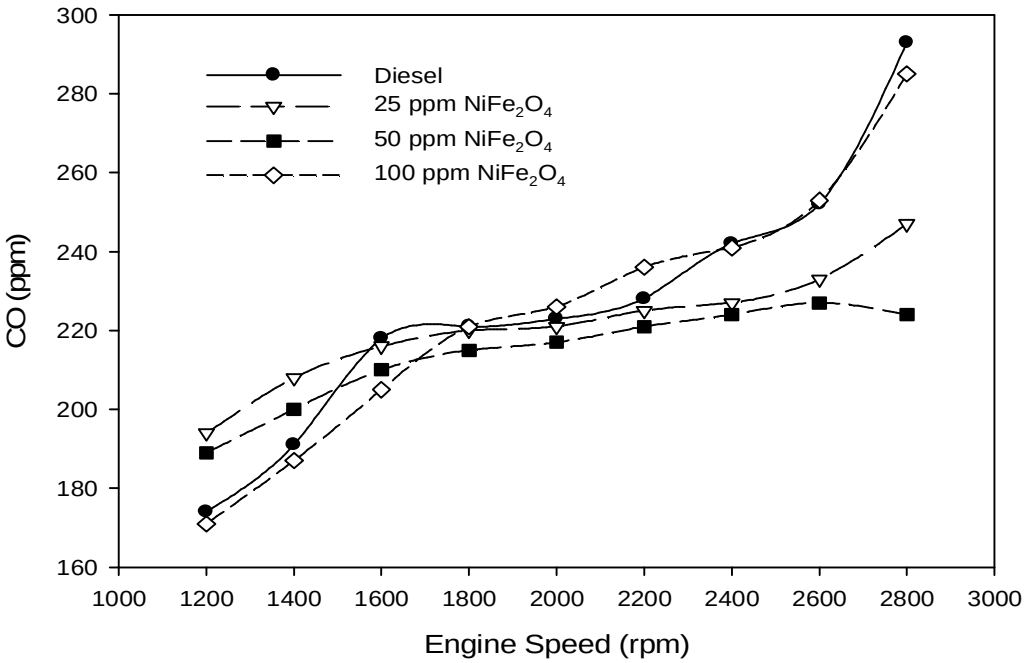


Figure 4.44. CO emission values of test fuels

Figure 4.45 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. $NiFe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm increased the CO_2 emissions values of the diesel fuel. The maximum CO_2 emission increase according to diesel fuel result is 6%, 27% and 14% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum CO_2 emission increase was obtained at 1600 rpm engine speeds for the 25 ppm and at 2400 rpm engine speed for the 50 and 100 ppm addition dosage. The average increment is 0.8%, 8.6% and 1.2% according to base fuel (diesel fuel) at the $NiFe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm respectively.

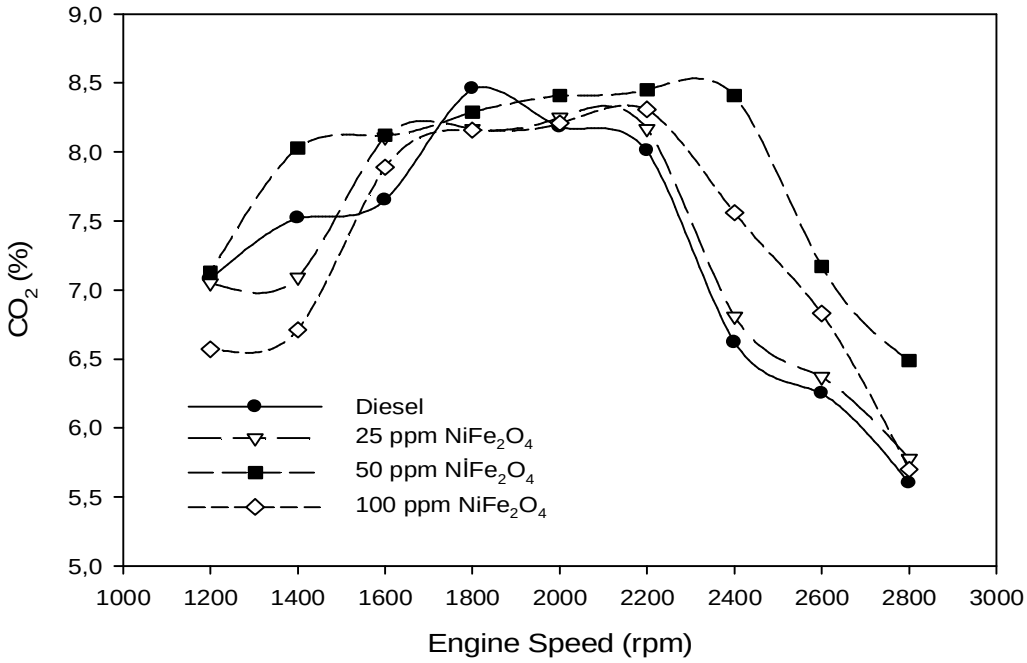


Figure 4.45. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.46. The maximum NO_x emissions were measured with the diesel fuel. $NiFe_2O_4$ nanoparticle addition dosage of 25, 50 and 100 ppm decreased the NO_x emissions with respect to diesel fuel. The maximum nitrogen oxides emission reduction according to diesel fuel result is 18.7%, 19.2% and 22.1% for the modified fuels at the nanoparticle addition dosage of 25, 50 and 100 ppm respectively. The maximum nitrogen oxides emission reduction was obtained at 1200 engine speed for the all modified fuels. The average reduction is 5.2%, 6.3% and 7.5% according to base fuel (diesel fuel) at the addition dosage of 25, 50 and 100 ppm respectively. Average nitrogen oxides (NO_x) emission reduction values increased with the increased dosage of nickel iron oxide nanoparticle addition in the diesel fuel.

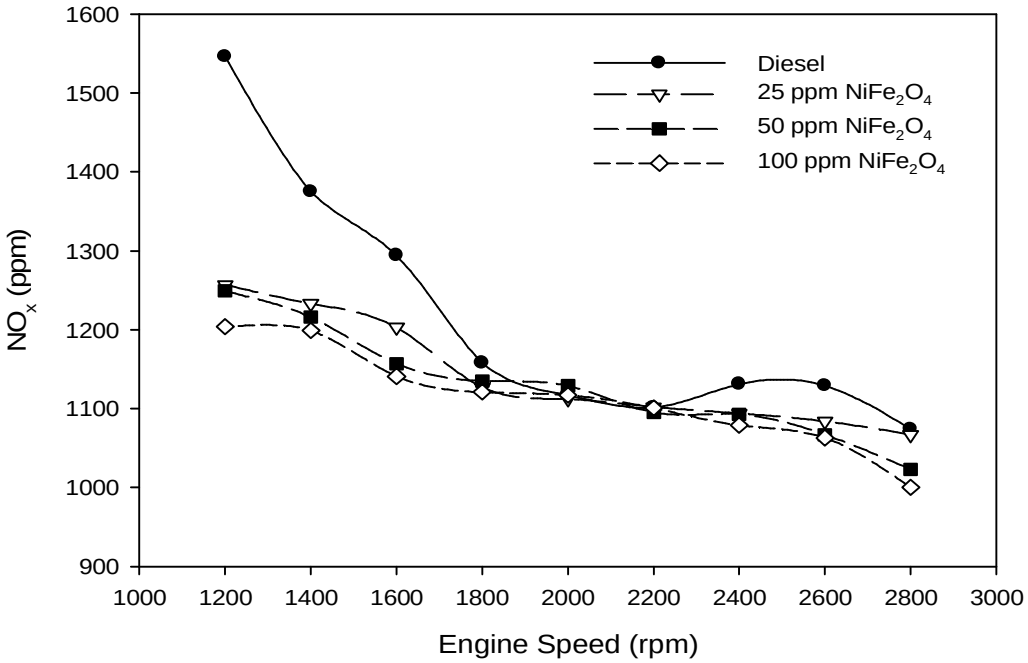


Figure 4.46. NO_x emission values of test fuels

4.10. Effects of Magnesium Oxide (MgO), Silicon Oxide (SiO_2) and Nickel Oxide (NiO) Nanoparticle Additives on Rapeseed Methyl Ester (RME) Fuel

4.10.1. Fuel Properties

The analysis of test fuels was conducted at the Çukurova University Mechanical Engineering Department Automotive Engineering Laboratories. Density, viscosity, flash point, cetane number, pour point characteristic was tested according to standards. Fuel properties of RME and modified RME fuels were given in Table 4.10. Also European biodiesel standard EN 14214 was given in Table 4.10.

Table 4.10. Fuel Properties of RME and Modified RME Fuels

Property	Units	EN 14214	RME	25 ppm SiO_2	50 ppm SiO_2	25 ppm MgO	50 ppm MgO	25 ppm NiO
Density at 15°C	kg/m³	860-900	896	895	896	896	895	896
Viscosity at 40°C	mm²/s	3.5-5.0	5.09	4.86	4.84	4.87	4.83	4.75
Flash point	°C	min 120	>180	>180	>180	>180	>180	>180
Cetane number	-	min 51	53.4	51.2	49.9	51.6	48.2	51.9
Pour Point	°C	Summer < 4.0 Winter < -1.0	-9	-8	-8	-8	-8	-8

Addition of different dosage of SiO_2, MgO and NiO nanoparticles has no noticeable effect on density value of rapeseed methyl ester (RME) fuel.

Kinematic viscosity of RME fuel was decreased with the addition of SiO_2, MgO and NiO nanoparticles at the dosage of 25 and 50 ppm. Viscosity value of modified fuels is 4.86 mm^2/s, 4.84 mm^2/s at the dosage of 25 and 50 ppm SiO_2, 4.87 mm^2/s, 4.83 mm^2/s at the dosage of 25 and 50 ppm MgO, 4.75 mm^2/s at the dosage of 25 ppm NiO nanoparticle additives respectively. Viscosity value of the RME fuel was decreased with the increase in the additive dosage of SiO_2, MgO nanoparticles. Viscosity results of modified fuels are in the acceptable range of European biodiesel standard EN 14214.

Flash point of the RME fuel and modified RME fuels with SiO_2, MgO and NiO nanoparticles addition is higher then 180 °C. Higher flash point temperatures are desirable for safe handling of the fuel. According to European biodiesel standard EN 14214 for biodiesel fuel a minimum flash point of 120 °C is required for safety. The flash point result represented that storage and transporting of modified RME fuels can be done safely.

Cetane number of the RME fuel showed decreasing trend with the addition of SiO_2, MgO and NiO nanoparticles. It was decreased to 51.2 and 49.9 at the dosage of 25 and 50 ppm SiO_2, 51.6 and 48.2 at the dosage of 25 and 50 ppm MgO, 51.9 at the dosage of 25 ppm NiO nanoparticle additives respectively. Cetane number is the ignition quality of a fuel. Decrease in the cetane number means decrease in the ignition quality of the fuel which will lead to poor combustion of the fuel in the

combustion chamber. According to European biodiesel standard EN 14214 for biodiesel fuel a minimum cetane number of 51 is required for good combustion. Cetane number of all modified fuels at the addition dosage of 25 ppm is in the limits of EN 14214.

Pour point of the RME fuel was slightly increased with the addition of SiO_2, MgO and NiO nanoparticles Pour point was recorded as -8°C for all modified fuels. This indicates that the addition of SiO_2, MgO and NiO nanoparticles has a little effect on the cold temperature properties of RME fuel.

4.10.2. Engine Performance

The brake power output of test fuels is shown in Figure 4.47. Power output values commonly increased with the addition of SiO_2, MgO and NiO nanoparticles to rapeseed methyl ester fuel. The increment is higher at higher engine speeds (between 2000 and 2800 rpm). It was observed that the maximum power values with all test fuels were obtained at an engine speed of 2400 rpm. The maximum brake power increase according to RME fuel result is 4.2% and 4.8% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 6.8% and 4.4% for the 25 and 50 ppm MgO and 4.4% for the 25 ppm NiO respectively. The maximum average brake power increase is 2.4% according to base fuel (RME fuel) at the addition dosage of 25 ppm MgO.

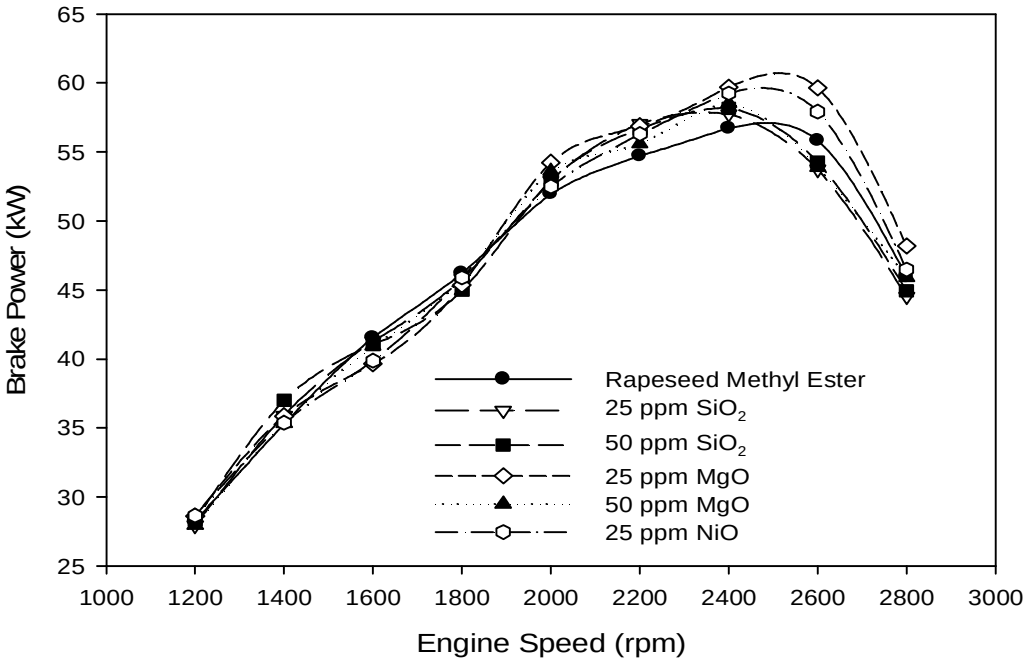


Figure 4.47. Brake power output versus engine speed for the test fuels

The torque output of test fuels is shown in Figure 4.48. Torque output values mostly increased with the addition of SiO_2, MgO and NiO nanoparticles to rapeseed methyl ester fuel. The maximum torque values for all fuels were obtained at engine speeds of 1800-2000 rpm. The maximum torque increase according to RME fuel result is 3.6% and 4.3% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 5.8% and 4.5% for the 25 and 50 ppm MgO and 3.4% for the 25 ppm NiO respectively. The maximum torque increase was obtained at 2400 rpm engine speed for the all modified fuels. The maximum average torque increase is 2.3% according to base fuel (RME fuel) at the addition dosage of 25 ppm MgO.

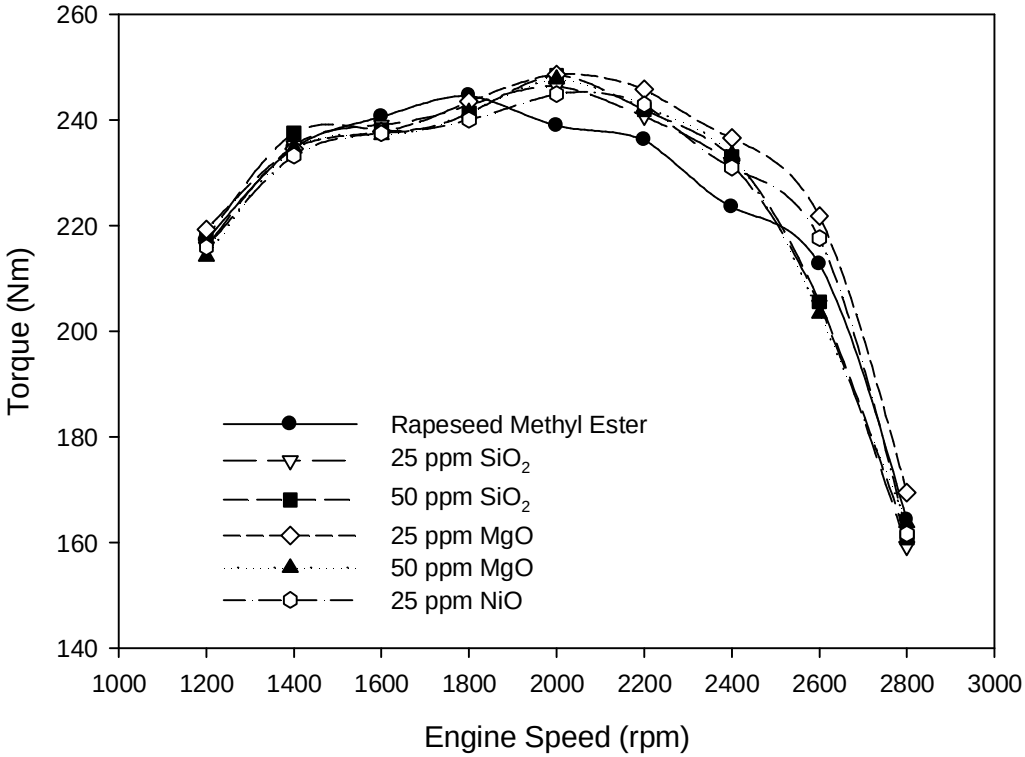


Figure 4.48. Torque output versus engine speed for the test fuels

4.10.3. Exhaust Emissions

Figure 4.49 demonstrates the carbon monoxide (CO) emissions versus engine speed with the variation of additive dosage. SiO_2, MgO and NiO nanoparticles with addition dosage of 25 and 50 ppm decreased the CO emissions of the rapeseed methyl ester fuel. The maximum CO emission reduction according to RME fuel result is 12% and 12.7% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 17.4% and 16.9% for the 25 and 50 ppm MgO and 12.4% for the 25 ppm NiO respectively. The average CO emission reduction is 10.4% and 7.8% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 4% and 1% for the 25 and 50 ppm MgO and 8.6% for the 25 ppm NiO respectively. The maximum average CO reduction is 10.4% according to base fuel (RME fuel) at the addition dosage of 25 ppm SiO_2.

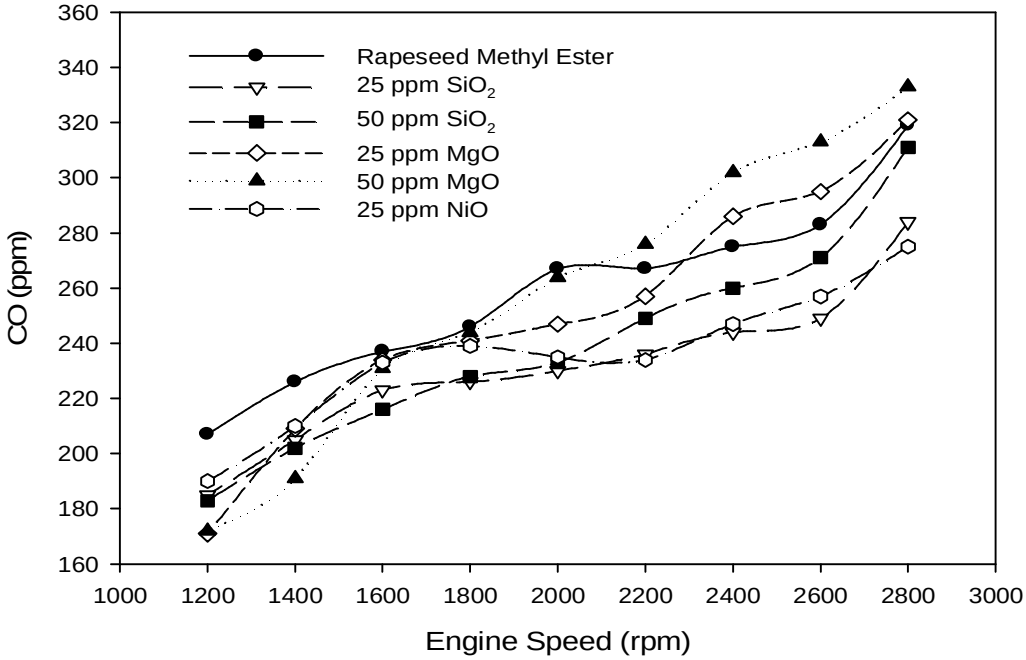


Figure 4.49. CO emission values of test fuels

Figure 4.50 illustrates carbon dioxide (CO_2) emissions of test fuels at different engine speeds. SiO_2, MgO and NiO nanoparticles increased the CO_2 emissions values of the RME fuel at the addition dosage of 25 and 50 ppm. The maximum CO_2 emission increase according to RME fuel result is 10.7% and 10.8% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 19.1% and 10% for the 25 and 50 ppm MgO and 18.6% for the 25 ppm NiO respectively. The average CO_2 emission increment is 2% and 2.7% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 7.4% and 1.6% for the 25 and 50 ppm MgO and 6.7% for the 25 ppm NiO respectively. The maximum average CO_2 emission increase is 7.4% according to base fuel (RME fuel) at the addition dosage of 25 ppm MgO.

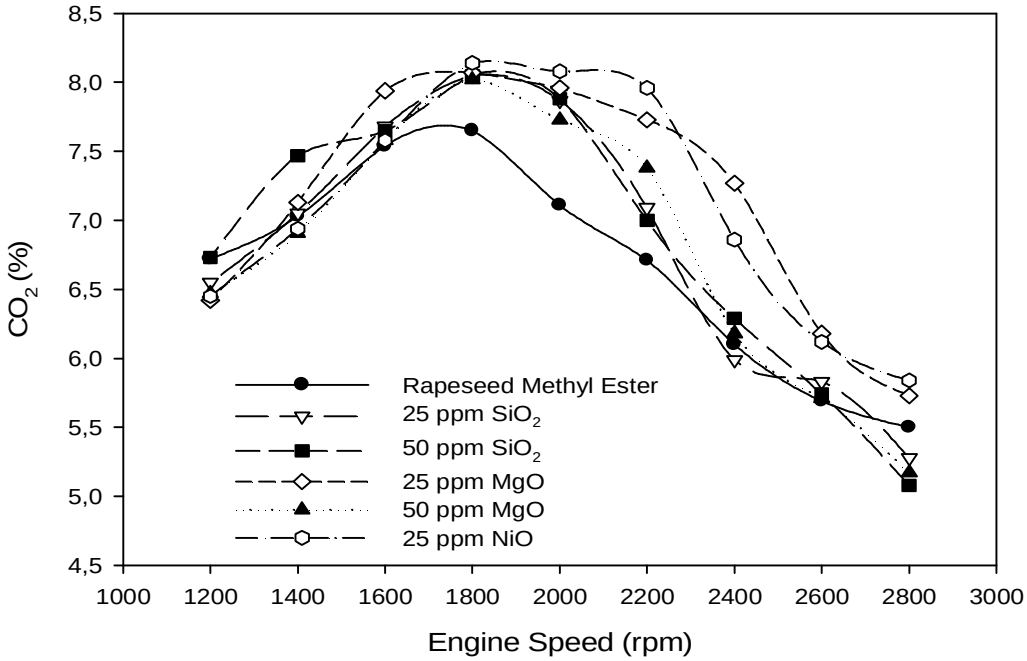


Figure 4.50. CO_2 emission values of test fuels

The variations of measured nitrogen oxides (NO_x) emissions values of test fuels with engine speed are demonstrated in the Figure 4.51. SiO_2, MgO nanoparticles addition dosage of 25 and 50 ppm decreased the NO_x emissions and NiO nanoparticle addition dosage of 25 ppm increased the NO_x emissions of rapeseed methyl ester fuel. The maximum nitrogen oxides emission reduction according to RME fuel result is 7.2% and 9.4% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 10.7% and 16.7% for the 25 and 50 ppm MgO respectively. The maximum nitrogen oxides emission increase is 9% for the modified fuel at the nanoparticle addition dosage of 25 ppm NiO. The average NO_x emission reduction is 0.4% and 3% for the modified fuels at the nanoparticle addition dosage of 25 and 50 ppm SiO_2, 2.2% and 7.2% for the 25 and 50 ppm MgO respectively. The average nitrogen oxides emission increase is 4.4% for the modified fuel at the nanoparticle addition dosage of 25 ppm NiO. The maximum average NO_x emission increase is 7.2% according to base fuel (RME fuel) at the addition dosage of 50 ppm MgO.

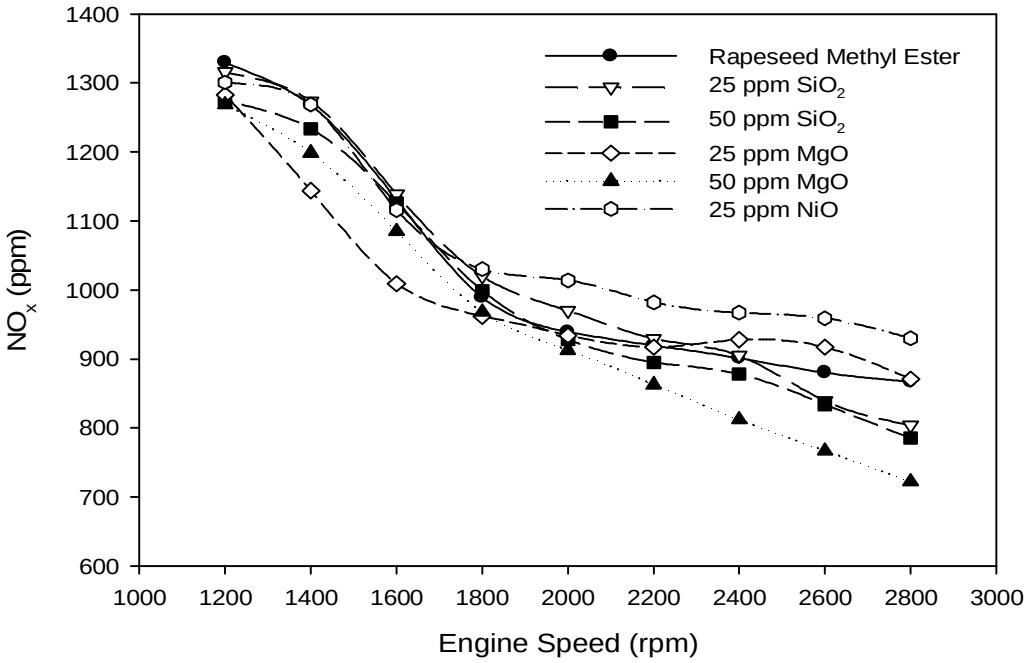


Figure 4.51. NO_x emission values of test fuels

5. CONCLUSIONS AND RECOMMENDATIONS

One of the methods to vary the physicochemical properties and combustion characteristics of a hydrocarbon fuel is the use of additives, which are found to be especially effective in nanoparticle form, due to the enhancement of the surface area to volume ratio. Consequently, nine different nanoparticle additives namely; MgO, Al_2O_3, TiO_2, ZnO, SiO_2, Fe_2O_3, NiO, $NiFe_2O_4$ and $Zn_{0.5}Ni_{0.5}Fe_2O_4$ were added to diesel fuel at the addition dosage of 25, 50 and 100 ppm and three of them namely MgO, SiO_2 and NiO were added to biodiesel fuel at the addition dosage of 25 and 50 ppm to investigate effects of nanoparticle additives on performance and exhaust emissions in a Compression Ignition Engine and on fuel properties of diesel and biodiesel fuel.

The density of diesel and biodiesel fuels does not show significant variation, due to the addition of nanoparticles. The viscosity of diesel fuel was found to increase with the addition of nanoparticles. All of the nanoparticles increased the viscosity value of diesel fuel. The maximum increment was obtained with NiO nanoparticle at the addition dosage of 100 ppm. All viscosity results of the modified diesel fuels with the addition of nanoparticles are in the limits of European petrodiesel standard EN 590. The viscosity of biodiesel fuel was found to decrease with the addition of MgO, SiO_2 and NiO nanoparticles. The maximum reduction was obtained with NiO nanoparticle at the addition dosage of 25 ppm. All of the viscosity results of the modified biodiesel fuels with the addition of nanoparticles are in the limits of European biodiesel standard EN 14214.

The flash point of diesel fuel, which is an indication of the volatility, was found to increase with the inclusion of the nanoparticle additives. All of the nanoparticle additives increased the flash point of diesel fuel. Higher flash point temperatures are desirable for safe handling of the fuel. According to European petrodiesel standard EN 590 for diesel fuel a minimum flash point of 55 °C is required for safety. The flash point result represented that storage and transporting of modified diesel fuels can be done safely.

The cetane number of diesel fuel, which is the ignition quality of a fuel, was found to decrease with inclusion of the nanoparticle additives except that SiO_2 nanoparticle. The cetane number of the diesel fuel with the addition of SiO_2 nanoparticle was increased. Cetane number of the biodiesel fuel was found to decrease with the addition of MgO, SiO_2 and NiO nanoparticles. Decrease in the cetane number means decrease in the ignition quality of the fuel which will lead to poor combustion of the fuel in the combustion chamber. An adequate cetane number is required for good engine performance. According to European petrodiesel standard EN 590 for diesel fuel and European biodiesel standard EN 14214 for a biodiesel fuel a minimum cetane number of 51 is required for good combustion. Cetane numbers of modified diesel fuels with the addition dosage of 25 ppm MgO (51.1) , 25 and 50 ppm NiO (54.4 and 51.6), 25, 50 and 100 ppm SiO_2 (56.1, 56.8 and 58.5) and 25 ppm ZnO (54) are in the limits of European petrodiesel standard EN 590. Cetane numbers of modified biodiesel fuels with the addition dosage of 25 ppm SiO_2 (51.2), MgO (51.6) and NiO (51.9) are in the limits of European biodiesel standard EN 14214.

No significant differences were observed in the pour points due to the addition nanoparticles to diesel fuel. This indicates that the addition of nanoparticles does not have any significant effect on the cold temperatures properties of diesel fuel and no strategic difference is required in the cold handling of the modified diesel fuels. Pour point of the biodiesel fuel was slightly increased with the addition of SiO_2, MgO and NiO nanoparticles. Pour point was recorded as -8°C for all modified biodiesel fuels. This indicates that the addition of SiO_2, MgO and NiO nanoparticles has a little effect on the cold temperature properties of biodiesel fuel.

Engine tests with the modified diesel fuels at different dosing levels (25, 50 and 100 ppm) of the additives showed an reduction in the torque and brake power output values of the engine except that nickel iron oxide and zinc oxide nanoparticle additives. Torque and brake power output values were increased with the addition of the nickel iron oxide ($NiFe_2O_4$) nanoparticle. The torque and brake power values of biodiesel fuel were found to slightly increase with the addition of MgO, SiO_2 and

NiO nanoparticles. The maximum average increase was obtained with MgO nanoparticle at the addition dosage of 25 ppm as 2.3%.

Carbon monoxide (CO) emission of the diesel fuel, which is a colorless lethal gas formed due to incomplete combustion of fuel air-mixture in the combustion chamber was found to decrease with the inclusion of the nanoparticle additives. The maximum average reduction was obtained with MgO nanoparticle at the addition dosage of 25 ppm as 12.2%. Carbon monoxide (CO) emissions of the biodiesel fuel were found to decrease with the addition of MgO, SiO_2 and NiO nanoparticles. The maximum average reduction was obtained with SiO_2 nanoparticle at the addition dosage of 25 ppm as 10.4%. Combustion remains incomplete due to two reasons, insufficient quantity of air supplied and lesser time allowed for completion of combustion process. Oxygen containing nanoparticles decrease the CO emissions of the diesel and biodiesel fuels by supplying extra oxygen to the fuel-air mixture in the combustion chamber.

Carbon dioxide (CO_2) emissions of the diesel fuel were found to decrease with the inclusion of the nanoparticle additives except that nickel iron oxide and zinc oxide nanoparticle additives. The maximum average reduction was obtained with MgO nanoparticle at the addition dosage of 100 ppm as 13.6%. Carbon dioxide (CO_2) emissions of the diesel fuel were increased with the addition of nickel iron oxide and zinc oxide nanoparticles. The maximum average increase was obtained with nickel iron oxide ($NiFe_2O_4$) nanoparticle at the addition dosage of 50 ppm as 8.6%. Carbon dioxide (CO_2) emissions of the biodiesel fuel were found to increase with the addition of MgO, SiO_2 and NiO nanoparticles. The maximum average increase was obtained with MgO nanoparticle at the addition dosage of 25 ppm as 7.4%.

Nitrogen oxides (NO_x) emissions of diesel fuel were found to decrease with the inclusion of the nanoparticle additives except that Al_2O_3 nanoparticle additive. The maximum average reduction was obtained with MgO nanoparticle at the addition dosage of 100 ppm as 16.7%. Nitrogen oxides (NO_x) emissions of the diesel fuel were increased with the addition of Al_2O_3 nanoparticle. The maximum average increase was obtained with Al_2O_3 nanoparticle at the addition dosage of 25 ppm as

4%. Nitrogen oxides (NO_x) emissions of biodiesel fuel were found to decrease with the addition of MgO, SiO_2 nanoparticles and increase with the NiO nanoparticle. The maximum average reduction was obtained with MgO nanoparticle at the addition dosage of 50 ppm as 7.2%. The reductions in NO_x emission of diesel and biodiesel fuels is due to complete combustion of modified fuels with the help of catalyst effect of nanoparticle additions which promotes heat transfer in the combustion chamber.

Comparing all the test results most efficient additives and dosing levels are determined for the diesel and biodiesel fuels; 25 ppm MgO, 50 and 100 ppm SiO_2 and 25 and 50 ppm NiO nanoparticle additives are determined as the most efficient additives for the diesel fuel. At the same time MgO and SiO_2 nanoparticles at the addition dosage of 25 ppm are determined as the most efficient additives for the biodiesel fuel.

Table 5.1. Reduction in the engine performance and emissions of diesel fuel

Additive	**Dosing Level**	**Torque**	**Brake Power**	**CO**	**CO_2**	**NO_x**	**Cost (TL/Liter)**
MgO	25 ppm	4.5%	3.8%	12%	2%	3%	0.022
SiO_2	50 ppm	5.0%	4.8%	4%	6%	7%	0.062
SiO_2	100 ppm	5.7%	5.5%	9%	4%	3%	0.124
NiO	25 ppm	0.9%	1.3%	5%	3.8%	8.4%	0.026
NiO	50 ppm	1.2%	1.5%	8%	1.8%	4%	0.052

Table 5.2. Change in the engine performance and emissions of biodiesel fuel

Additive	**Dosing Level**	**Torque Increase**	**Brake Power Increase**	**CO Reduction**	**CO_2 Increase**	**NO_x Reduction**	**Cost (TL/Liter)**
MgO	25 ppm	2.3%	2.4%	3.4%	7%	2.2%	0.024
SiO_2	25 ppm	-	-	10.4%	2%	0.4%	0.033

Fuel properties of the diesel fuel with 25 ppm MgO, 25 and 50 ppm NiO and 25 and 50 ppm SiO_2 nanoparticles satisfy the European petrodiesel standard EN 590. Fuel properties of the biodiesel fuel with the MgO and SiO_2 nanoparticle additions at the addition dosage of 25 ppm satisfy the European biodiesel standard EN 14214.

Additional cost of adding 25 ppm MgO nanoparticle to the diesel fuel is 0.022 TL per liter, 50 and 100 ppm SiO_2 is 0.062 and 0.124 TL per liter and 25 and

50 ppm NiO nanoparticle is 0.026 and 0.052 TL per liter. Extra cost of addition of 25 ppm MgO and SiO_2 is 0.024 and 0.033 TL per liter respectively.

As a result of the study, 25 ppm MgO, 50 and 100 ppm SiO_2 and 25 and 50 ppm NiO nanoparticles can be used as an additive for diesel fuel to decrease the exhaust emissions in the compression ignition engines. In addition to this MgO and SiO_2 nanoparticle additions at the addition dosage of 25 ppm can be used as additives for the biodiesel fuel to decrease the exhaust emissions of diesel engines.

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