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Experimental investigation of the effect of fuel oil, graphene and HHO gas addition to diesel fuel on engine performance and exhaust emissions in a diesel engine

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HIGHLIGHTS

- An improvement in emissions and performance was expected by adding graphene and HHO gas to the DF40 fuel mixture.
- Adding fuel oil to diesel fuel generally deteriorates engine performance and emissions.
- HC and CO emissions decreased, and CO_2 and NO_x emissions increased with graphene and HHO gas.

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ABSTRACT

Today, research for alternative fuels continues due to the increasing energy demand, exhaust emission restrictions, and depletion of fossil fuels. It is important to use diesel engines for the opening of new oil fields in Turkey and for the utilization of fuel oil to be produced in these oil fields. In this study, pure diesel (D) diesel 60% and fuel oil 40% (DF40) were supplied by volume with an ultrasonic mixer. 50 (DF4050 N) and 100 ppm (DF40100 N) graphene have been added to eliminate fuel oil's adverse combustion effects by keeping the fuel oil constant. In addition, HHO gas was added to improve the combustion even more with a flow rate of 5 (DF4050N5H and DF40100N5H) and 10 (DF4050N10H and DF40100N10H) lt/min into the intake manifold by using the HHO generator. Experiments were carried out at 3000 RPM constant speed at 3.2, 6.4, 7.9, and 12.8 Nm engine torque without any modification on the diesel engine. The effects of these mixtures on combustion performance and exhaust emissions were investigated. Exhaust gas temperature and emissions were measured in the experiments. According to the measurements, thermal efficiency, brake specific energy consumption (BSEC), HC, CO, CO_2, particle emission, and NO_x emission values are given. Brake specific energy consumption (BSEC), CO, HC, and particle emissions decreased, and thermal efficiency, NO_x, CO_2, and exhaust gas temperature increased with the engine torque value increased as a result of the experiments. Thermal efficiency and CO_2 emission decreased, and BSEC, exhaust gas temperature, HC, CO, NO_x, and particulate emissions increased by adding fuel oil to diesel fuel. The thermal efficiency was increased by adding graphene and HHO gas from the intake manifold to DF40 fuel. The

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thermal efficiency improved, and emissions decreased with the more addition of graphene and HHO gas. Adding HHO gas improved thermal efficiency significantly at the 12.8 Nm engine load. With the addition of graphene and HHO gas to DF40 fuel, the BSEC value was improved at high torque values. The effect of improving thermal efficiency is also understood from the decrease in CO emissions and the increase in CO_2 emissions. HC and PM emissions decreased with the addition of graphene and HHO gas. It was observed that NO_x and exhaust gas temperature increased with increasing thermal efficiency.

Nomenclature

ATDC	After Top Dead Center
BSEC	Brake Specific Energy Consumption
BTDC	Before Top Dead Center
CA	Crankshaft Angles
CO	Carbon Monoxide
CO_2	Carbon Dioxide
D	100% Diesel
DF40	60% Diesel 40% Fuel Oil
DF40100 N	60% Diesel 40% Fuel Oil +100 ppm Nano graphene
DF40100N10H	60% Diesel 40% Fuel Oil +100 ppm Nano graphene+ 10 lt/min HHO HHO Generator, To split water (H_2O) into Hydrogen and Oxygen
DF40100N5H	60% Diesel 40% Fuel Oil + 100 ppm Nano graphene+ 5 lt/min HHO
DF4050 N	60% Diesel 40% Fuel Oil + 50 ppm Nano graphene
DF4050N10H	60% Diesel 40% Fuel Oil + 50 ppm Nano graphene+ 10 lt/min HHO
DF4050N5H	60% Diesel 40% Fuel Oil + 50 ppm Nano graphene+ 5 lt/min HHO
ECAS	Emission Control Areas
EDS	Energy Dispersive Spectrometry
FTIR	Fourier Transform Infrared
g	Grams
h	Hour
HC	Hydro Carbon
HHO	Hydrogen–Hydrogen–Oxygen
HRR	Heat Release Rate
ID	Ignition Delay
IMO	International Maritime Organization
kHz	Kilohertz
kW	Kilowatt
MARPOL	International Convention for the Prevention of Pollution from Ships
MJ	Mega Joule
Nm	Newton-meter
NO_x	Nitrogen Oxide
°C	Centigrade degrees
PM	Particle Emission
PPM	Parts Per Million
RPM	Revolution Per Minute
SEM	Scanning Electron Microscopy
SO_x	Sulfur Oxide
TDC	Top Dead Center

1. Introduction

Coal, which plays an important role in supporting industrial, social and economic developments in the world, is a common fossil energy source in nature [1]. Despite the environmental pollution problems, it is predicted that coal will continue to be used soon. Coal consumption worldwide in 2022 has exceeded 8 billion tons [2]. Coal is a fossil fuel that causes emissions considered within the scope of greenhouse gas [3] Petroleum-based diesel, gasoline and natural gas fuels such as coal are also considered important causes of environmental pollution [4].

The increase in greenhouse gas emissions threatens climates and biodiversity [5]. Since hydrogen fuel does not contain carbon, it is recommended as a clean fuel against global warming [6]. Using hydrogen-fueled vehicles instead of fossil fuels in automotive technologies and using hydrogen fuel cells effectively reduce carbon emissions [7–10].

Diesel engines are widely used in many fields, such as transportation, logistics, agriculture, and maritime [11]. Diesel engines; Due to their advantages such as high efficiency, low fuel consumption, and high power, it has been used so widely [12,13]. However, the intensive use of diesel engines causes the depletion of fossil fuel resources, increasing energy costs and air pollution. Therefore, more economical and environmentally friendly alternative fuels should be investigated [14,15].

Research is being carried out using alcohols, biofuels, natural gas, and hydrogen in diesel engines. Hydrogen is preferred among the gaseous fuels studied because it has a high calorific value and does not contain carbon [[16–19]]. Hydrogen provides complete combustion due to its wide combustion range and high combustion rate. However, the high auto-ignition temperature of hydrogen (853 K) prevents it from being used as the sole fuel in diesel engines. Therefore, diesel engines can be operated in dual fuel mode with hydrogen [19,20]. Hydrogen has a low molecular weight and is the lightest element in nature. It has a storage problem due to its low density [21]. Various studies have reported that hydrogen gas injection can improve diesel engine performance and reduce exhaust pollutants.

Biodiesel production from sustainable sources for diesel engines is considered a good alternative to fossil fuels [22]. Biodiesel is a renewable alternative energy source produced from materials such as animal, waste edible, and vegetable oils [23–27]. Research on biodiesel; shows that using biodiesel in diesel engines can reduce CO, CO_2, PM, and HC emissions and increase NO_x emissions [28–32].

The most important factor determining diesel engine emissions is fuel properties. Different fuel additives are used to improve fuel quality [33,34]. Nanoparticles; It is used as an additive that improves the physicochemical properties of the fuel, such as kinematic viscosity, flash point, and pour point, as well as thermo-physical properties such as thermal conductivity, mass distribution, surface area-volume ratio [35,36]. In addition to metal oxides such as aluminum, iron, and titanium, polymeric materials, carbon, and ceramics are widely used nanoparticles [32,37–43]. There are studies investigating the effect of nanoparticles on diesel engine performance and emissions. Selvan et al. [44] investigated the effects of diesterol (diesel-biodiesel-ethanol) fuel, cerium oxide nanoparticles, and carbon nanotubes on performance and emissions in a variable compression ratio engine. The addition of cerium oxide nanoparticles to diesel fuel increased the oxidation rate. It has been observed that the flash point and kinematic viscosity increase with the addition of cerium oxide nanoparticles to the biodiesel fuel [45]. Adding cerium nanoparticles to the diesterol mixture increased the cylinder gas pressure. It has been observed that carbon nanotubes and cerium oxide nanoparticles improve combustion and reduce exhaust emissions. Silva et al. [46] investigated the effects of adding titanium dioxide nanoparticles to biodiesel in diesel engines on performance and emissions. The test results showed that combustion efficiency increased and CO, CO_2, and NO_x emissions decreased significantly [47]. However, titanium dioxide nanoparticles are toxic and adversely affect human health [48,49]. Mirzajanzadeh et al. [50] investigated the changes in engine performance and exhaust emissions by adding cerium oxide-carbon nanotube nano-catalyst to diesel-biodiesel mixtures. Experiment results; showed that engine performance improved, and fuel consumption, HC, CO, NO_x, and soot emissions decreased. It has also been reported that cerium oxide nanoparticles are harmful to health. Gumus et al. [51] investigated the effects of aluminum oxide and copper oxide nanoparticles on diesel engine performance and emissions. Experimental results: Adding aluminum and copper oxide nanoparticles to diesel fuel increases engine performance and reduces exhaust emissions. They also reported that aluminum oxide is harmful to health. EL-Seesy et al. [52,53] investigated the effect of adding nano-graphene oxide and graphene nanoplatelet to diesel-biodiesel blends on diesel engine performance and emissions. Experiment results; showed that engine power and NOx emissions increased, and specific fuel consumption, CO, and HC emissions decreased. Studies on the addition of nanoparticles to diesel and biodiesel fuels; show that metallic-based additives and multi-walled carbon nanotube additives positively affect engine performance and emissions. Reducing ignition delay and multi-walled carbon nanotubes having highly reactive surfaces provide cleaner combustion. It is seen that these additives act as catalysts in the combustion zone and significantly reduce emissions [54]. Graphene oxide is more environmentally friendly than other additives, with its low toxic effect and high energy density [22,52,55,56]. Graphene has been preferred because it is more advantageous than other nanoparticles and because it is more environmentally friendly than other nanoparticles. In many studies, the additive in the range of 25–100 ppm was used. For this reason, graphene was preferred as a nanoparticle additive in this study.

Fuel oil is generally used in the industry for heat and electricity generation and in the transportation sector for powering ships engaged in international shipping. The International Maritime Organization (IMO) issued the International Convention for the Prevention of Pollution from Ships (MARPOL) in the 1970s. In 1997, the MARPOL protocol was accepted to reorganize this contract. One of the annexes of this protocol; limits the sulfur content of the fuel oil used in the marine industry. According to the protocol, the decision taken to prevent sulfur oxide (SOx) emissions from ships has been accepted by the European Parliament and Council Directive (EU 2016/802). It has been revised several times in recent years. Implementing these restrictions could not reduce the amount of fuel oil used in maritime due to the increasing international trade in recent years. It is seen that the amount of use remains at the same level. On January 1, 2020, "IMO 2020" entered into force. With this regulation, the maximum sulfur content in fuel oil used by ships is determined as 0.5% m/m, except for Emission Control Areas (ECAS). In ECAS, the upper limit is regulated as 0.1% m/m [57].

It is seen that there are many studies on alternative fuels or additives to diesel fuel. It is seen that fuel oil is used especially in ship diesel engines. It can be said that the use of fuel oil together with diesel fuel in diesel generators is an important issue. With the increase in the number of vehicles using diesel fuel and the limited source of fossil fuels, the search for alternative fuels to diesel fuel is increasing due to the low proportion of diesel fuel in refined crude oil. For this reason, it can be said that it is necessary to make some improvements in order to use fuel oil, which is especially used in ship diesel engines, in new generation diesel engines. These improvements are made especially to make fuel oil fuel similar to diesel fuel. It is thought to improve the particle emission and combustion characteristics of the fuel by adding graphene to the diesel fuel oil fuel mixture. It is also considered to reduce carbon emissions with the addition of HHO. In addition, HHO gas addition and nanoparticle studies with the HHO generator continue intensively. In this study, the effects of diesel-fuel oil-graphene-HHO gas mixtures on engine performance and exhaust emissions were experimentally investigated.

2. Material and method

2.1. *Test fuel*

The diesel fuel, fuel oil, and graphene (20–40 nm) used in the experiments were obtained from commercially available companies. The supplied fuel oil was first processed for 3 h in a magnetic stirrer heater at a stirring speed of 600 rpm and a temperature of 70 °C. The heated and mixed fuel oil was passed through the diesel fuel filter. The treated fuel oil was mixed volumetrically into the diesel fuel. For this purpose, 40% of fuel oil was mixed into diesel. The mixture created is expressed with the abbreviation DF40 in the graphics. For this purpose, the first fuel mixture (DF40) was obtained by mixing the fuel oil into the diesel fuel in a magnetic stirrer at a temperature of 50 °C for 24 h, at a stirring speed of 600 rpm. After resting on this fuel mixture for 24 h, it was observed that the fuel oil did not sink to the bottom. The mixing ratio of fuel oil into diesel fuel was determined by the amount of precipitate in the diesel fuel. 40% is the rate that does not form a precipitate. Graphene at 50 ppm and 100 ppm ratios was added to this obtained fuel mixture, and it was subjected to a mixing process for 1 h at 40 kHz wave speed in an ultrasonic mixer. As a result of this process, the fuel mixtures used in the experiments were prepared. The chemical and physical properties of the fuels and fuel mixtures used in the experiments are given in Table 1.

2.2. HHO generator

In this study, a UCR-brand hydrogen generator was used. The preferred brand continues its commercial activities and already assembles hydrogen kits for vehicles. The parts and system that make up the HHO generator used in the experiments are given in Fig. 1. The HHO generator used consists of a total of 8 titanium plates. Depending on the current, the production capacity of the HHO generator changes. The current-dependent generation capacity of the HHO generator is given in Fig. 2. HHO production capacity can be adjusted by changing the current amount with the control panel. Despite this, a sensitive natural gas valve and a Flow brand flow meter were placed at the end of the HHO generator, and the gas flow to be supplied to the intake manifold was controlled. In addition, a spark check valve is mounted on the line to prevent a spark from entering the intake manifold.

2.3. Experimental setup

Engine experiments were carried out in a single-cylinder, compression ignition engine. Technical specifications of the engine used in the experiments are given in Table 2.

An electric dynamometer with a maximum power of 26 kW and a torque absorption capacity of 80 Nm and a maximum speed of 5000 rpm (±50) was used to conduct engine experiments. A mixing chamber is designed before the intake manifold for better mixing of gaseous fuel with air. This mixing chamber is positioned 40 cm ahead of the engine's intake manifold. Thus, the presence of the HHO + air mixture is continuously added at five l/min, and ten l/min is provided behind the engine's intake valves. All engine experiments measured exhaust gas emission values (CO, CO_2, HC, smoke, NO_x) with a Mobydic Combi exhaust emission device. The measuring ranges of the exhaust emission device are shown in Table 3. During the study, the fuel consumption values of the liquids were determined in mass with a precision balance. Changes in exhaust gas emissions were measured instantaneously with a K-type thermocouple. The schematic view of the experimental setup is shown in Fig. 3.

The total uncertainties of the data obtained in the experiments were calculated using the Kline McClintock method [58,59]. The accuracy of the measurement tools and the total uncertainties calculated are given in Table 4.

2.4. Test procedure

Engine tests were repeated for each fuel mixture at a constant engine speed of 3000 RPM at engine loads of 3.2 Nm, 6.4 Nm, 7.9 Nm, and 12.8 Nm. Before starting the experiments, the engine was run with diesel fuel, and after the engine was warmed up, the pilot fuel was started. Afterward, the liquid fuel amount of the engine was reduced by giving HHO gas in the engine, and after obtaining the desired power value of the engine, all measurements were recorded, and the data obtained were discussed in the next section.

3. Experimental results

In the experimental study, the measurements and calculations obtained for four different engine loads and eight different fuels at constant speed are given in this section. Thermal efficiency, exhaust gas temperature, brake specific energy consumption (BSEC), CO, CO_2, HC, NO_x, and particulate emissions are given.

Fig. 4 shows changing the thermal efficiency-different fuel mixture and torque values. It is seen that the thermal efficiency generally increases with increasing torque value. The lowest thermal efficiency value was 8.98% at 3.2 Nm torque for the DF40 fuel mixture. The highest calculated thermal efficiency value was realized at 12.8 Nm torque value for the DF40100N10H fuel mixture. In experiments conducted at constant engine speed, it is thought that the reason for the increase in thermal efficiency in all fuel mixtures as the torque increases is the improvement in combustion.

The highest thermal efficiency for each load condition was obtained in the DF40100N10H fuel mixture when the graph is examined in terms of different fuel mixtures. The addition of fuel oil to diesel fuel reduced thermal efficiency. The lowest thermal efficiency value was measured with the DF40 fuel mixture. Thermal efficiency decreased by adding fuel oil to diesel fuel (DF40 fuel mixture) at all torque values. The highest thermal efficiency value was calculated as 25.3% at 12.8 Nm torque with the DF40100N10H fuel mixture. The lowest thermal efficiency was calculated as 8.98% at 3.2 Nm torque for the DF40 fuel mixture. The thermal efficiency of DF40 fuel decreased by 6.92% compared to diesel fuel at 12.8 Nm torque. There was an increase in thermal efficiency for all other fuel mixtures. The highest increase in thermal efficiency was realized in the DF40100N10H fuel mixture with 24.48%. An efficiency decrease occurred with adding fuel oil to diesel fuel under all load conditions. This is because fuel oil has more negative properties than diesel fuel in terms of lower calorific value, density, viscosity and cetane number. Thermal efficiency increased with the addition of graphene to DF40 fuels. This increase occurred due to the intense energy content of graphene. In addition, the end-of-combustion temperature of the hydrogen in the HHO gas can be explained by its heating value and the fact that the oxygen in the HHO partially improved the combustion [60,61].

Fig. 5 shows the BSEC change for different fuel mixtures and torque values. It is seen that the BSEC value decreases for all fuel mixtures as the torque value increases. The lowest BSEC value was 12.68 MJ/g/kWh with the DF40100N5H fuel mixture at 12.8 Nm torque. It is thought that the reason for the decrease in the BSEC value in all fuel mixtures as the torque increases is the improvement in combustion with the increase in thermal efficiency. This situation; In cases where the BSEC value tends to decrease, it can be understood from the increasing trend in thermal efficiency.

Table 1 – Physical and chemical properties of experimental fuels.

Propertis	Calorific value (MJ/kg)	Kinematic viscosity (cSt) at 40 °C	Fire point °C	Flash point °C	Density(kg/m^3) at 15 °C
Diesel Fuel (D)	42.5	3.38	67	55	840
Fuel Oil (F)	44.45	26.4	55	78	975
DF40	43.3	11.8	60	63	918
DF4050 N	43.25	11.9	63	63	918
DF40100 N	43.21	12.1	66	65	921

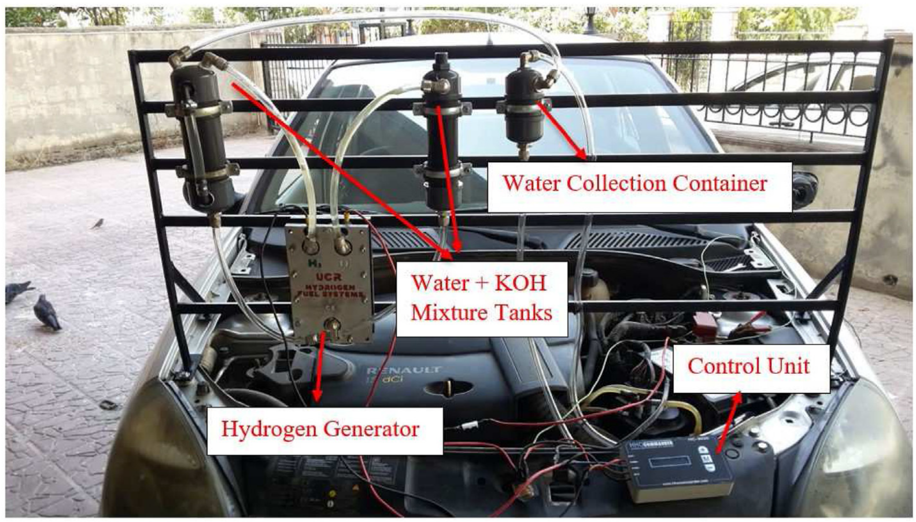

Fig. 1 – The hydrogen generator and its components.

In studies with gaseous fuels, values are given to determine the amount of BSEC rather than the specific fuel consumption. Here, the total energy consumption value is mentioned. The fact that there is no decrease in the amount of BSEC despite the fact that HHO gas is released at ten l/min can be explained by a decrease in combustion efficiency. This can be explained by the fact that the amount of HHO gas sent from the intake manifold decreases the volumetric efficiency. On the other hand, five l/min caused a decrease in the amount of BSEC. In this case, it is thought that the amount of oxygen in the HHO gas effectively maintains the volumetric efficiency [60,62].

Fig. 6 shows the change in CO emissions for different fuel mixtures and torque values. There was a decrease in CO emissions with increasing torque for all fuel mixtures. The highest CO emission value was measured as 0.65% at 3.2 Nm torque values for the DF40 fuel mixture. The lowest CO emission value was measured as 0.18% at 12.8 Nm torque for the DF40100N10H fuel mixture. In experiments conducted at

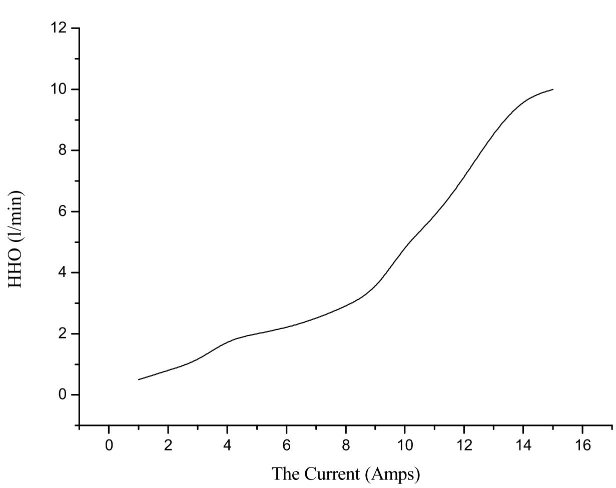

Fig. 2 – The production capacity of the HHO generator.

Table 2 – Technical characteristics of the experimental engine.

Engine	Four strokes, direct injection, air-cooled, and naturally aspirated
Model	186 FAG
Number of cylinders	1
Intake system	Naturally aspirated
Bore x stroke	86 × 70 mm
Total displacement	406 cm^3
Compression ratio	18:1
Maximum power	7 kW (3600 rpm)
Pressure of injection	19.6 ± 0.49 Mpa
Fuel delivery advance angle	21 (°CA) BTDC

Table 3 – Measurement range of gas analyzer and calculated uncertainties.

Component	Measurement Range	Resolution	Accuracy %
CO (% vol.)	0–10.00	0.001	±0.01
CO_2 (% vol.)	0–18.00	0.01	±0.05
HC (ppm)	0–9999	1	±0.01
O_2 (% vol.)	0–22.00	0.01	±0.04
Lambda	0.50–9.99	0.001	±0.0001
NO (ppm)	0–5000	≤1	±0.1
Smoke Opacity (%)	0–100	0.1	±0.1

Table 4 – Uncertainty about measuring device.

Measured parameter	Measurement device	Accuracy
Engine Speed	Incremental encoder, rpm	±1%
Fuel mass	Precision scale, g	±0.1%
Exhaust gas temperature	Thermocouple, °C	±1%
Time measurement	Digital chronometer, s	±1%
Gas Flow	Mass flow meter, l/min	±1%
Calculated Results	**Uncertainty**	
Power	±1.17%	
BSEC	±1.54%	
Engine Torque	±1.22%	

constant engine speed, it is thought that the reason for the decrease in CO emissions in all fuel mixtures as the torque increases, regardless of the fuel used, is the improvement in combustion with the increase in thermal efficiency. This situation; In cases where CO emission tends to decrease, graphs showing an increase in thermal efficiency and a decrease in BSEC value support the trend.

When the graph is examined in terms of fuel, it is seen that the highest CO values for each torque value were measured for the DF40 fuel mixture, and the addition of graphene and HHO gas to the DF40 fuel mixture reduces CO emissions. It is seen that the lowest CO values were measured with the DF40100N10H fuel mixture. It is seen that the CO emission decreases as the graphene and HHO gas ratio in the mixture increases at all torque values. For the torque value of 12.8 Nm, the CO emission of DF40 fuel increased by 283% compared to diesel fuel. With the addition of 50 ppm graphene to the DF40 fuel mixture, there was a 10.8% decrease compared to the DF40 fuel. Adding 100 ppm graphene to the DF40 fuel mixture resulted in a 19.6% decrease compared to DF40 fuel. Compared to DF40 fuel, the DF4050N5H fuel mixture has a 32.6% reduction in CO emissions. DF4050N10H fuel mixture has a 39.1% reduction in CO emissions compared to DF40 fuel. A decrease of 54.3% was achieved in the DF40100N5H fuel mix. With the DF40100N10H fuel mixture, there was an improvement in CO emissions of 60.9% compared to the DF40 fuel. For a torque value of 12.8 Nm, the CO emission of the DF40100N10H fuel mixture increased by 50% compared to diesel fuel. However, at a torque value of 3.2 Nm, a 31.5% reduction in CO emission

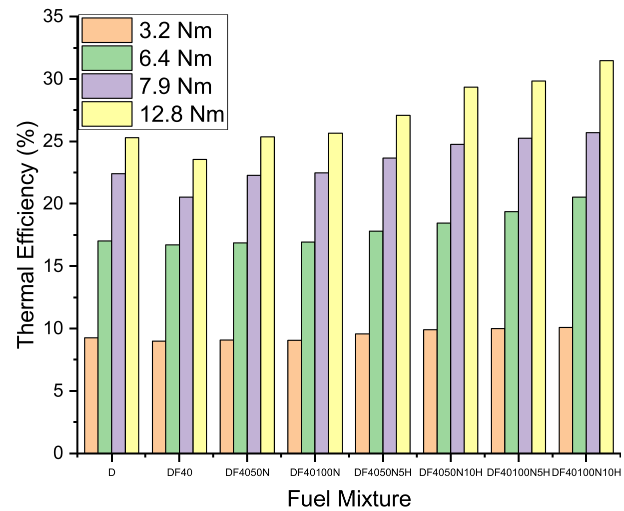

Fig. 4 – Variation of thermal efficiency for different torque values and fuel mixtures.

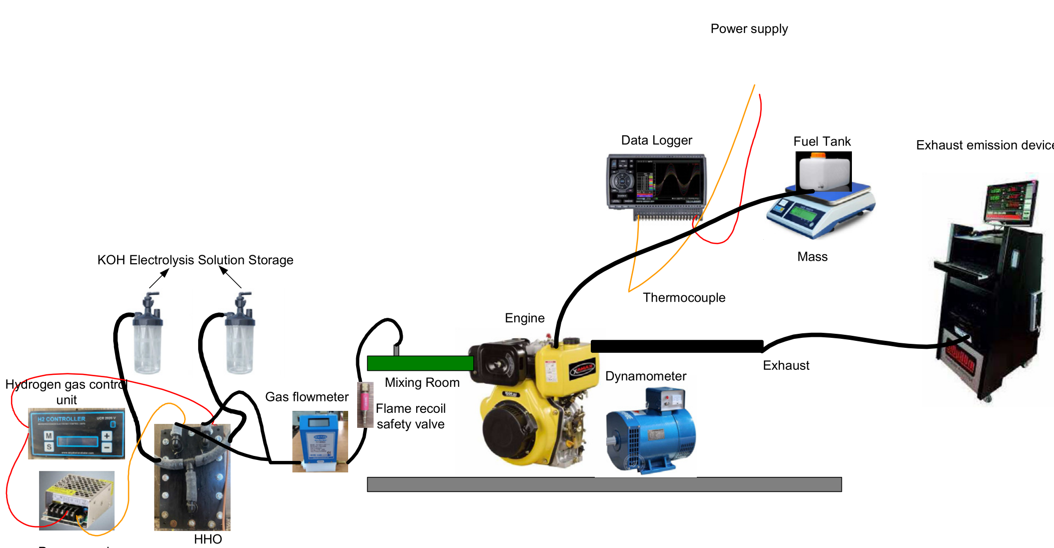

Fig. 3 – Schematic view of the experimental setup.

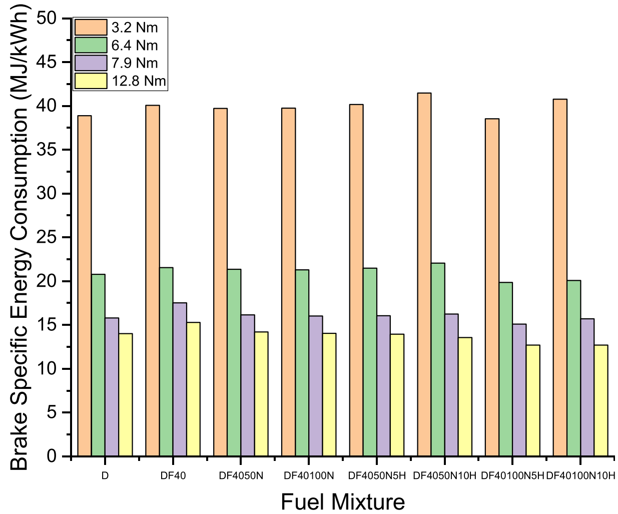

Fig. 5 – BSEC changing different torque and fuel mixtures.

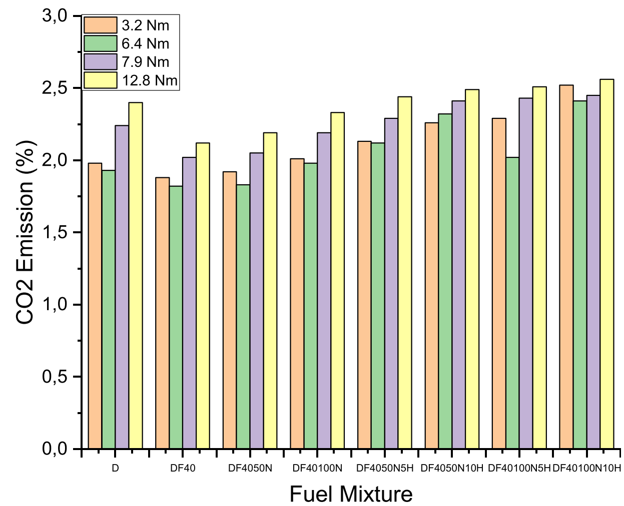

Fig. 7 – CO_2 emission variation at different torque values of different fuel mixtures.

was observed in the DF40100N10H fuel mixture compared to diesel fuel. The increase in CO emissions with the addition of fuel oil to diesel fuel can be understood from the decrease in combustion efficiency. At the same time, it can be expressed that fuel oil viscosity and density cetane number are worse than diesel. With the addition of graphene, there was a decrease in CO emissions. The reduction at high loads by adding HHO gas is due to improved combustion. The decrease in low torque values is more limited in CO emission. Because HHO gas in the intake manifold increases, the fresh air is throttled [63,64].

Fig. 7 shows the CO_2 emission change for different fuel mixtures and torques. An increase in CO_2 emission has occurred for all fuel mixtures with the increase in torque. The highest CO_2 emission value was measured as 2.56% at 12.8 Nm torque for the DF40100N10H fuel mixture. The lowest CO_2 emission value was measured as 1.82% at 6.4 Nm torque for the DF40 fuel mixture. In this situation, The trend of decreasing CO emission is supported by graphs showing the trend of increase in thermal efficiency and decrease in BSEC value.

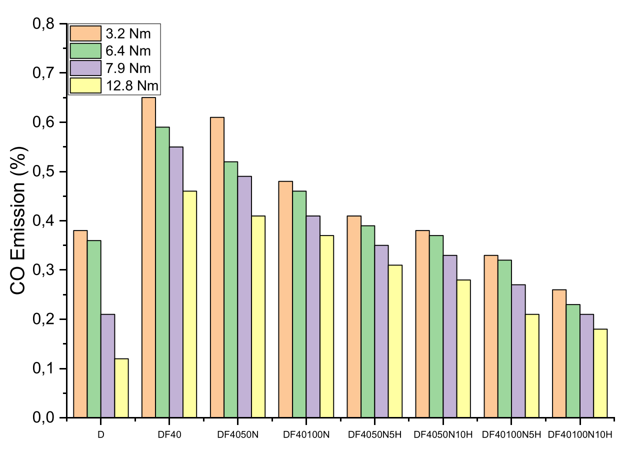

Fig. 6 – CO emission variation at different torque values of different fuel mixtures.

When the graph is examined in terms of fuel, the lowest CO_2 values for each torque value were measured for the DF40 fuel mixture, and the addition of graphene and HHO gas to the DF40 fuel mixture increased the CO_2 emission. The highest CO_2 emission was measured with the DF40100N10H fuel mixture. The CO_2 emission increased as the graphene and HHO gas ratio in the mixture increased at all torque values. The CO_2 emission of DF40 fuel decreased by 11.66% compared to diesel fuel at 12.8 Nm torque value. Adding 50 ppm graphene (DF4050 N) and 100 ppm graphene (DF40100 N) to the DF40 fuel mixture increased CO_2 emission by 3.3% and 9.9%, respectively, compared to DF40 fuel. The DF4050N5H and DF4050N10H fuel mixture has increased CO_2 emission by 15.1% and 17.5%, respectively, compared to DF40 fuel. The DF4050N5H and DF4050N10H fuel mixture has increased CO_2 emission by 18.4% and 20.8%, respectively, compared to DF40 fuel. CO_2 emission of DF40100N10H fuel mixture increased by 6.6% compared to diesel fuel at 12.8 Nm torque. With the addition of fuel oil to diesel fuel, the decrease in CO_2 emission is understood from the decrease in combustion efficiency. At the same time, it can be expressed that fuel oil viscosity, density, and cetane number are worse than diesel. CO_2 emissions increased with the addition of graphene. Due to the carbon content of graphene, it provides energy and improves combustion, resulting in an improvement in CO_2 emissions. It can be said that the combustion efficiency is much more improved with the addition of HHO gas, which increases CO_2 emissions much higher [64,65].

Fig. 8 shows the HC emission change for different fuel mixtures and torque values. A decrease in HC emission has occurred with the torque increase for all fuel mixtures. The highest HC emission value was 148 ppm at 3.2 Nm torque for the DF40 fuel mixture. The lowest HC emission value was 41 ppm at 12.8 Nm torque for diesel fuel. It is thought that the reason for the decrease in HC emission in all fuel mixtures as

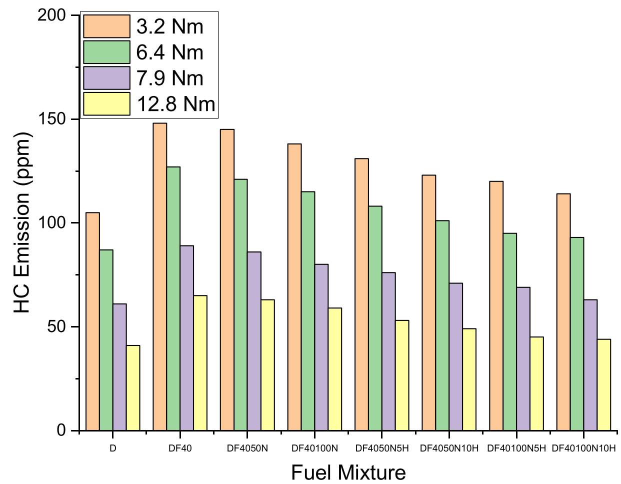

Fig. 8 – HC emission variation at different torque values of different fuel mixtures.

the torque increases, regardless of the type of fuel used, is the improvement in combustion with the increase in thermal efficiency. In this situation, The decrease in CO emission and BSEC value, the increase in thermal efficiency, and CO2 emission support the graphs.

When the graph is examined in terms of fuel, the lowest HC emission values for each torque value were measured in the tests using diesel fuel. With the addition of fuel oil to diesel fuel, there has been a serious increase in HC emissions. HC emission decreased by adding graphene and HHO gas to the DF40 fuel mixture. The highest HC emission was measured in tests with DF40 fuel. At all torque values, HC emission decreased as the graphene and HHO gas ratio in the mixture increased.

For 12.8 Nm torque value, HC emission of DF40 fuel mixture increased by 58.5% compared to diesel fuel. Adding 50 ppm (DF4050 N) and 100 ppm graphene (DF40100 N) to the DF40 fuel mixture reduced 3% and 9.2%, respectively, compared to the DF40 fuel. Adding 50 ppm graphene and HHO gas 5lt/min DF4050N5H and 10 l t/min DF4050N10H fuel mixtures reduced 18.5% and 24.6%, respectively, HC emissions compared to DF40 fuel. Adding 100 ppm graphene and HHO gas 5 l t/min DF40100N5H and 10 l t/min DF40100N10H fuel mixtures reduced 30.8% and 32.4%, respectively, compared to DF40 fuel. HC emission of DF40100N10H fuel mixture increased by 7.3% compared to diesel fuel at 12.8 Nm torque. Adding fuel oil to diesel fuel increases HC emission is also understood from the decrease in combustion efficiency. At the same time, it can be expressed that fuel oil viscosity, density, and cetane number are worse than diesel. HC emissions decreased with the addition of graphene. Due to the carbon content of graphene, it provides energy and improves combustion, resulting in an improvement in HC emission. It can be said that the combustion efficiency is much more improved with the addition of HHO gas, and the improvement in HC emission is also more significant than graphene [64,66].

Fig. 9 shows the change in particle emission for different fuel mixtures and torque values. There was a decrease in particulate emissions for all fuel mixtures with increased torque. The highest particulate emission value was 18.5 mg/m3 at 3.2 Nm torque for the DF40 fuel mixture. The lowest particulate emission value was 7.5 mg/m3 at a torque of 12.8 Nm for diesel fuel. In the experiments carried out at constant engine speed, graphs showing an increase in the thermal efficiency and CO_2 emission support the reason why the particulate emission decreases in all fuel mixtures as the torque increases, regardless of the fuel used.

When the graph is examined in terms of fuel, the lowest particle emission values for each torque value were measured in the tests using diesel fuel. With the addition of fuel oil to diesel fuel, there has been a severe increase in particulate emissions. With the addition of graphene and HHO gas to the DF40 fuel mixture, there was a decrease in particulate emissions. The highest particle emission was measured in tests with DF40 fuel for all torque values. Particle emission decreased as the graphene and HHO gas ratio in the mixture increased at all torque values. For 12.8 Nm torque value, particulate emission of DF40 fuel increased by 96% compared to diesel fuel. Adding 50 ppm graphene (DF4050 N) to the DF40 fuel mixture resulted in a 2% reduction compared to DF40 fuel. Adding 100 ppm graphene (DF40100 N) to the DF40 fuel mixture resulted in a 4.7% reduction compared to DF40 fuel. Compared to DF40 fuel, the particle emission of the DF4050N5H fuel mixture decreased by 7.5%. Compared to DF40 fuel, the DF4050N10H fuel mixture decreased by 11.6% particulate emissions. DF40100N5H fuel mixture achieved a 13.6% reduction. With the DF40100N10H fuel mixture, there was a 23.1% reduction in particulate emissions compared to the DF40 fuel. For the 12.8 Nm torque value, a 50.6% increase in particulate emission of DF40100N10H fuel mixture compared to diesel fuel was observed. The increase in particulate emissions with the addition of fuel oil to diesel fuel can be expressed as the viscosity, density, and cetane number of fuel oil fuel being worse than diesel. With the addition of graphene, there was a decrease in particle emissions. Because of the carbon content of graphene, it provides energy and improves combustion, improving particle emission. It can be

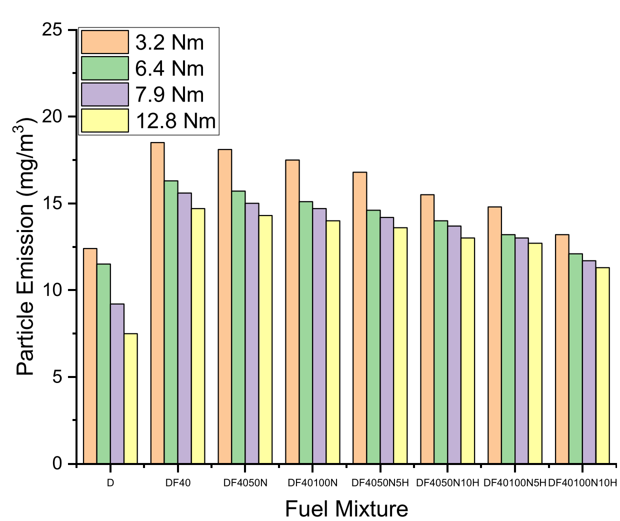

Fig. 9 – Particulate emission variation at different torque values of different fuel mixtures.

said that with the addition of HHO gas, the combustion efficiency is much more improved, and there is also an improvement in particle emission [67].

Fig. 10 shows the NO_x change for different fuel mixtures and torque values. The highest NO_x emission was measured at 153 ppm at 12.8 Nm torque for the DF40100N10H fuel mixture. The lowest NO_x emission value was measured at 80 ppm at 3.2 Nm torque for diesel fuel. It is thought that NO_x emission increases with increasing torque, regardless of the fuel used, because of the improvement in combustion with the increase in thermal efficiency.

When the graph is analyzed in terms of fuel, the lowest NO_x emission values for each torque value were measured at diesel fuel. With the addition of fuel oil to diesel fuel, NOx emissions increased. The NO_x emission increased by adding graphene and HHO gas to the DF40 fuel mixture. The highest NO_x emission was measured with the DF40100N10H fuel mixture for all torque values. NO_x emission increased by increasing the mixture's graphene and HHO gas ratio at all torque values. For 12.8 Nm torque value, NO_x emission of DF40 fuel increased by 2.6% compared to diesel fuel. Adding 50 ppm graphene (DF4050 N) to the DF40 fuel mixture resulted in a 6% reduction compared to DF40 fuel. Adding 100 ppm graphene (DF40100 N) to the DF40 fuel mixture resulted in a 0.8% reduction compared to DF40 fuel. NO_x emission of the DF4050N5H fuel mixture increased by 9.4% compared to DF40 fuel mixture. There was an increase of 12.9% in DF4050N10H fuel mixture NO_x emission compared to DF40 fuel. An increase of 19.8% was achieved in the DF40100N5H fuel mixture. With the DF40100N10H fuel mixture, there was a 31.9% reduction in NO_x emissions compared to the DF40 fuel. For a torque value of 12.8 Nm, a 35.4% increase in NO_x emission was observed in the DF40100N10H fuel mixture compared to diesel fuel. The increase in NO_x emission with the addition of fuel oil to diesel fuel can be expressed as the viscosity, density, and cetane number of fuel oil being worse than diesel fuel. NO_x emissions increased with the addition of graphene [68]. As graphene provides energy due to its carbon content and improves combustion, NO_x emission has increased. It can be said that with the addition of HHO gas, the combustion efficiency is much better, and there is an increase in NO_x emission [69,70].

Fig. 11 shows the variation of the exhaust gas temperature of different fuel mixtures with torque. As the torque increased, the exhaust gas temperature increased. While the lowest exhaust gas temperature was measured in diesel fuel, the highest exhaust gas temperature was obtained in the DF40100N10H fuel mixture. The lowest exhaust gas temperature value was measured as 189 °C in the test performed with diesel fuel at 3.2 Nm torque. The highest exhaust gas temperature was measured as 594 °C for a torque value of 12.8 Nm for the DF40100N10H fuel mixture. In the experiments performed at constant engine speed, it is thought that the reason for the increase in the exhaust gas temperature in all fuel mixtures as the torque increases, regardless of the type of fuel used, is the improvement in combustion. The increase in thermal efficiency and NO_x emissions and the decrease in HC, CO, and PM emissions and BSEC support the increasing trend of exhaust gas temperature.

When the graph is examined in terms of fuel, the lowest exhaust gas temperature values for each load condition were measured in the tests using standard diesel fuel. It is seen that the exhaust gas temperature increases with the addition of fuel oil to diesel fuel. It is seen that the lowest exhaust gas temperature value in the tests performed was measured in the tests performed with diesel fuel. It is seen that the exhaust gas temperature increases as the amount of graphene and HHO gas in the mixture increase at all torque values. The highest exhaust gas temperature value in the tests was measured as 594 °C in the test at 12.8 load position with DF40100N10H fuel mixture. The lowest exhaust gas temperature value was measured as 189 °C for the 3.2 Nm torque value made with diesel fuel. For 12.8 Nm torque value, there was a 2.5% increase in the exhaust gas temperature of DF40 fuel compared to diesel fuel. The addition of 50 ppm graphene (DF4050 N) to the DF40 fuel mixture resulted in an increase of 3.3% compared to diesel fuel. Adding 100 ppm graphene (DF40100 N) to the DF40 fuel mixture increased by 4.2% compared to diesel. An increase of 6.3% was achieved in the

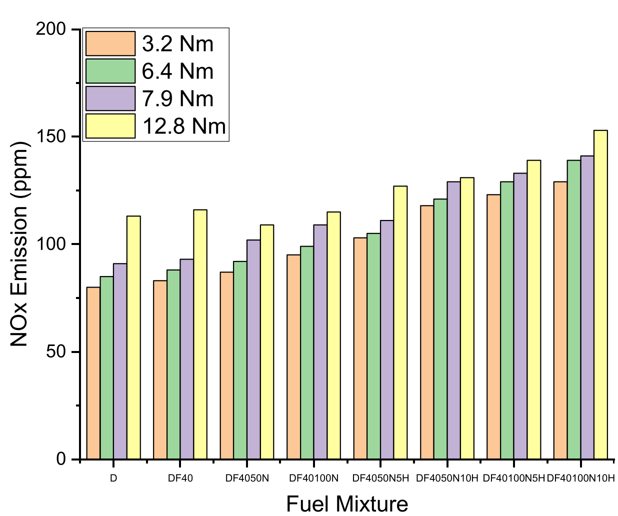

Fig. 10 – NO_x emission variation at different torque values of different fuel mixtures.

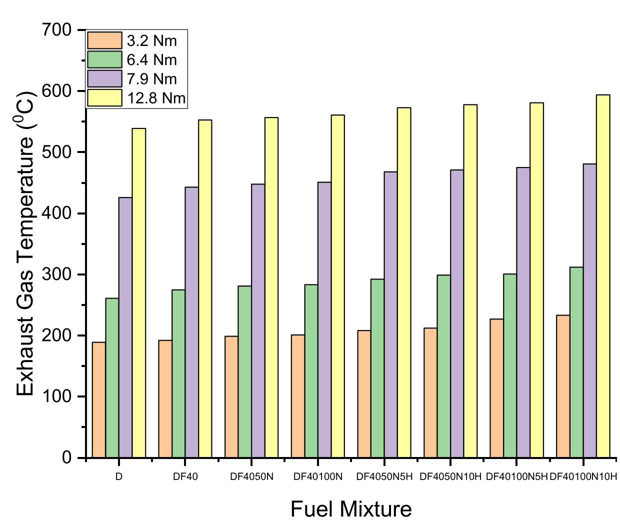

Fig. 11 – Exhaust gas temperature variation at different torque values of different fuel mixtures.

exhaust gas temperature of the DF4050N5H fuel mixture compared to the diesel. There was a 7.2% increase in the exhaust gas temperature of the DF4050N10H fuel mixture compared to diesel. An increase of 7.8% was achieved in the DF40100N5H fuel mixture. 10% compared to diesel fuel with DF40100N10H fuel mixture. There was an increase in the exhaust gas temperature. The reason for the increase in the exhaust gas temperature with the addition of fuel oil to the diesel fuel can be expressed as that the properties of the fuel oil fuel, such as viscosity, density, and cetane number, are worse than diesel. The reason for the increase in the exhaust gas temperature with the addition of graphene is that the carbon content of the graphene provides energy and improves combustion, so an increase in the exhaust gas temperature has occurred. It can be said that with the addition of HHO gas, the thermal efficiency is much better, and is a higher increase in the exhaust gas temperature [71,72].

4. Conclusion

In this study, the effect of HHO gas addition from the intake manifold with graphene to eliminate the negative effects of fuel oil addition to diesel fuel was experimentally investigated. In line with the results obtained, the following evaluation was carried out;

- With the addition of fuel oil to diesel fuel, a decrease in thermal efficiency was observed at all torque values. The thermal efficiency increased by adding graphene and HHO gas to DF40 fuel. Especially with the addition of HHO gas, a significant increase in thermal efficiency occurred.
- With the addition of fuel oil to diesel fuel, all torque values increased in the BSEC value. While the BSEC value is expected to decrease by adding graphene and HHO gas to the DF40 fuel mixture, this decrease occurred only at high torque values. Adding graphene and HHO gas at low torque values increased the BSEC value.
- With the addition of fuel oil to diesel fuel, there has been an increase in CO emissions and a decrease in CO_2 emissions. There was an increase in CO_2 emission and thermal efficiency and a decrease in CO emissions by adding graphene and HHO gas to the DF40 fuel mixture.
- HC and particle emissions increased by adding fuel oil to diesel fuel. HC and particulate emissions were decreased by adding graphene to the DF40 fuel mixture. There was a decrease in HC, and particulate emissions were achieved with the addition of HHO gas. HC and particulate emissions of DF40100N10H fuel mixture were higher than diesel. It can be said that the addition of fuel oil fuel affects HC and particulate emissions very much.
- With the addition of fuel oil to diesel fuel, NO_x and exhaust gas temperature increased. Although some species in the fuel oil reduce the thermal efficiency, the exhaust gas temperature and NO_x emission increased due to the increase in the maximum combustion temperature. It is understood that combustion efficiency has increased from the improvement in thermal efficiency and the increase in CO_2 emissions by adding graphene to the DF40 fuel mixture. Since this means that the maximum combustion temperature increased, NO_x and exhaust gas temperature increased.
- As a result of the study, it is understood that adding fuel oil affects negatively. With the addition of graphene and HHO gas, this negativity was tried to be eliminated. It was observed that the addition of HHO gas at low torques had a negative effect on the volumetric efficiency. It is thought that efficiency can be improved at low torques by adjusting the flow rate of the HHO generator.
- Although it is understood that the thermal efficiency will be increased by increasing the HHO generator even more at high torques, the exhaust gas temperature and NO_x emissions will be limited in this regard.

When crude oil is processed worldwide, fuels such as 23% diesel, 42% gasoline, and 4% fuel oil are produced. Considering that diesel is the most commonly used fuel among these produced fuels, it is thought that there will be a problem in diesel fuel supply after a certain period of time. It has become necessary to search for an alternative and cheap fuel to diesel fuel. An alternative fuel to diesel fuel has been studied by adding fuel oil to diesel fuel. Fuel oil's combustion efficiency and emission values are known to be worse than diesel due to density and viscosity. It is aimed to create cleaner combustion by adding nanographene to improve combustion and emission. In addition, this study targeted and realized the improvement of emissions by reducing the carbon content in the fuel with the addition of HHO. It has been clearly demonstrated that there is an improvement with the addition of graphene and HHO. In this sense, its parameters such as density and viscosity should be improved to use fuel oil as an alternative to diesel fuel. This can be achieved in future studies by adding pure hydrogen, oxygenated fuels, and cost-effective nanoparticles with thermal value. It is foreseen that fuel oil can be used as an alternative fuel to diesel fuel with these additions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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