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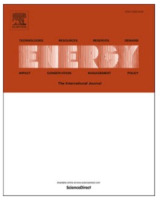

Effect of using borax decahydrate as nanomaterials additive diesel fuel on diesel engine performance and emissions

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ABSTRACT

Today, the increase in fuel consumption with the increasing number of vehicles has increased the efforts to make the engines more efficient. Diesel engines are subject to severe restrictions due to the emission problem. Although there is an emission problem, it is widely used especially in freight transportation. Many studies on diesel engines emission problems are made by academicians and manufacturers. In this sense, many studies have been carried out by adding nanomaterials to diesel fuel to reduce emissions in diesel engines. In this study, borax decahydrate as a fuel additive was studied in a diesel single-cylinder engine. Borax decahydrate was dissolved in 500 ml of methanol, 5 gr, 15 gr and 25 gr, and methanol was added to 10% diesel. To be 90% Diesel +10% Methanol (D90M10) 90% Diesel 10% Methanol + 1 gr Borax decahydrate (D90M10B1) 90% Diesel 10% Methanol + 3 gr Borax decahydrate (D90M10B2) 90% Diesel 10% Methanol + 5 gr Borax decahydrate (D90M10B3) four different fuel mixtures were tested. The experimental test measured in-cylinder pressure, heat release rate, fuel consumption, power, torque, exhaust gas temperature, smoke opacity, and exhaust emissions. Due to the rich oxygen content of borax decahydrate, it has been observed to reduce emissions, excluding NO_x emissions. There was an increase in exhaust temperature, nitrogen oxides (NOx), and carbon dioxide (CO_2) emissions and a serious decrease in HC, CO, brake-specific fuel consumption, and smoke opacity values. Studies should be expanded and enriched with different mixing ratios and usage patterns of boron-doped fuels in the future.

1. Introduction

Due to the increase in the world population, the development of technology and the increase in the level of welfare, the demand for vehicles is increasing day by day. With the increasing number of vehicles, studies to reduce engine emissions have increased due to the mandatory emission standards. Research for cleaner environmentally friendly fuel or cheaper fuel are increasing day by day. In this sense, there are currently studies on adding nanoparticles to diesel fuel. It is known that nanoparticles increase combustion efficiency and reduce emission values.

Nanoparticles generally have sizes ranging from 1 to 100 μm. Metals such as Ag, Cu, Mg, Mn [1], semi-metals such as boron [2] and metal oxides such as Al_2O_3, CeO_2, CuO, Fe_2O_3, Fe_3O_4, MgO, MnO, TiO_2, ZnO are used as additives to diesel engines in literature [3]. It is especially used in energetic carbon-based nanoparticles that can give energy when burned apart from these metals and metal oxides. Due to its carbon origin, carbon nanotubes contribute to the energy amount of the fuel by providing heat release during combustion [4]. Aalam et al. investigated the effect of adding 25 and 50 ppm carbon nanotubes to diesel fuel on engine performance and emissions. In-cylinder pressure, heat release rate, thermal efficiency, hydrocarbon (HC) and carbon monoxide (CO) emissions increased and brake-specific fuel consumption and smoke opacity values decreased with adding carbon nanotubes to diesel fuel [5]. Singh and Bharj studied adding 50, 100 and 150 ppm carbon nanotubes to 83% Diesel, 15% water, 2% surfactant [6] and 78% diesel, 20% water, 2% surfactant [7]. HC, NOx, CO and brake-specific fuel consumption values decreased with carbon nanotube surfactant and water-added diesel fuel mixtures. Pressure increase rate and thermal efficiency increased. In addition, it has been stated that there is a severe decrease in engine noise with carbon nanotube water and surfactant added to diesel fuel. They suggested that water, surfactant, and carbon nanotube can be used as additives to diesel fuel without any

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Nomenclature

D90M10	10% Diesel. To be 90% Diesel +10% Methanol
D90M10B1	90% Diesel 10% Methanol +1 gr Borax decahydrate
D90M10B2	90% Diesel 10% Methanol +3 gr Borax decahydrate
D90M10B3	90% Diesel 10% Methanol +5 gr Borax decahydrate
NOx	Nitrous Oxide
CO_2	Carbon Dioxide
$Na_2B4O7\cdot10H_2O$	Borax Decahydrate
HC	Hydro Carbon
CO	Carbon Monoxide
BTDC	Before Top Dead Center
P–V	Pressure-Volume Diagram
HRR	Heat Release Rate
FTIR	Fourier Transform Infrared
EDS	Energy Dispersive Spectrometry
SEM	Scanning Electron Microscopy
CA	Crankshaft Angles
ATDC	After Top Dead Center
TDC	Top Dead Center
ID	Ignition Delay
BSFC	Brake Specific Fuel Consumption

modification to increase diesel engine performance. Basha and Anand experimentally studied the addition of aluminum and carbon nanotubes to biodiesel fuel obtained by transesterification from jatropha in a diesel engine. They investigated 25 ppm and 50 ppm addition of only aluminum, only carbon nanotubes and a mixture of carbon nanotubes and aluminum to biodiesel fuel. In particular, the highest thermal efficiency was obtained in the mixture of two nanoparticles. An increase in performance and a decrease in emissions were obtained with two nanoparticles [8]. Afzal et al. investigated the effects of produced from scum oil biodiesel, alcohol and silver nanoparticles on diesel engine performance and emissions. First of all, diesel + biodiesel mixtures were tested and the best diesel + biodiesel mixture was determined. Then, the performances of diesel fuel and biodiesel + alcohol blends were compared. Finally, the addition of silver nanoparticles to the 60% diesel + biodiesel mixture was evaluated for two different injection pressures and crank angles. It has been determined that silver nanoparticle does not affect engine performance, but provide a decrease in emissions [9]. Saraee et al. investigated the effect of 10, 20 and 40 ppm silver nanoparticles added to diesel fuel on diesel engine performance and emissions. There was a significant decrease in emissions with silver nanoparticles addition. There has been considerable improvement in combustion and thermal efficiency. In particular, there was a decrease in fuel consumption [10]. Balamurugan et al. studied the effect of adding copper nanoparticles and soybean biodiesel to diesel fuel on diesel engine performance and emissions. Experiments were carried out by adding 10% soybean biodiesel and 1.5% by mass of 30 nm and 42 nm copper nanoparticles to diesel fuel. Significantly, engine performance has been increased with the addition of copper nanoparticles. There was also a reduction in NO_x and smoke opacity emissions [11]. Gürü et al. carried out experiments by adding 12 μmol of synthetic magnesium blended biodiesel to 10% diesel fuel in a diesel engine at full load and at different speeds. There was no significant change in engine torque with the addition of biodiesel and synthetic magnesium. Fuel consumption has increased due to the low calorific value of biodiesel. There was a decrease in smoke and CO emissions and an increase in NO_x emissions [12]. Çelik et al. investigated the effect of adding 4,8,12 and 16 ppm manganese to diesel fuel on a diesel single-cylinder engine performance and emissions for constant speed and different loads. The best improvement in engine torque was achieved with 12 ppm manganese. In addition, the highest reduction in brake-specific fuel consumption was obtained with 12 ppm manganese. There was an increase in NO_x and exhaust gas temperature and a decrease in CO, HC and smoke emissions with the addition of manganese [13]. Many studies have been carried out on carbon nanotubes as metal powders. At the same time, it has been seen that there are more studies in the literature on the addition of metal oxides to diesel fuel as an additive. Chaichan et al. performed tests by dissolving aluminium oxide in water and adding it to diesel fuel at five different rates in a diesel engine at full load-different speeds and at different loads-constant RPM. An increase in brake thermal efficiency and a decrease in brake-specific fuel consumption were obtained with the maximum addition of 10% of aluminium oxide and water mixture to diesel fuel. CO_2 emissions increased and CO, HC, NO_x and PM emissions decreased with 10% aluminium oxide and water mixture [14]. Chen et al. investigated adding 25 ppm, 50 ppm and 100 ppm silicon oxide, aluminium oxide and carbon nanotubes to diesel fuel effects on engine performance and emissions at four different loads in a diesel engine. Carbon nanotube, silicon oxide and aluminium oxide increased diesel engine performance, respectively. The highest increase was with carbon nanotubes. In emissions, especially in HC emissions, aluminium oxide has been reduced by 1.7 times than diesel fuel [15]. Gümüş et al. firstly investigated changes in fuel properties by adding 25 ppm, 50 ppm, 75 ppm and 100 ppm aluminium oxide to diesel fuel. The most suitable mixture was determined to be 50 ppm and diesel engine performance and emissions were investigated by adding 50 ppm aluminium oxide and copper oxide to the diesel fuel. It has been determined that aluminium oxide gives better results than copper oxide in engine performance and exhaust emissions [16]. Saraee et al. investigated by adding 10 ppm, 20 ppm and 40 ppm cerium oxide to diesel fuel at 10–30 nm size affect engine performance and emissions. The improvement in engine performance with the addition of cerium oxide resulted in a decrease in exhaust emissions. They also developed a prediction model by defining experimental data with artificial neural networks. It has been seen that the developed model can be used to estimate engine performance and emissions for close results given to experimental results [17]. Ooi et al. experimentally studied the addition of cerium oxide, graphene oxide, and single-walled carbon nanotube nanoparticles to 25 ppm diesel fuel in a diesel single-cylinder engine. The increase in engine performance and decrease in emissions were mostly achieved with single-walled carbon nanotubes. The experimental results obtained suggested using single-walled carbon nanotubes and graphene oxide as fuel additives [18]. Vairamuthu et al. experimentally carried out by adding 20 ppm, 40 ppm and 60 ppm cerium oxide to a mixture of 100% Punnai biodiesel and 50% Punnai biodiesel-50% diesel fuel compared with diesel fuel in a diesel engine with three, four and five nozzle holes and different sizes. It has been suggested that adding 40 ppm of cerium oxide in a mixture of injectors with five nozzle holes and 50% Punnai biodiesel +50% diesel from many different parameters creates the ideal situation [19]. Venkatesu et al. investigated the effect on engine performance and emissions by adding six ppm copper oxide and aluminum oxide to diesel fuel. An increase in engine performance and a decrease in exhaust emissions were obtained by adding copper oxide and aluminum oxide to diesel fuel. However, aluminum oxide performed better than copper oxide [20]. Sahoo and Jain investigated the effect on diesel engine performance and emissions by adding copper oxide to diesel fuel at a concentration of 0.5% with a magnet at three different positions on the fuel line. It has been observed that the effect of a magnet placed on the fuel line and the addition of copper oxide to diesel fuel improve engine performance and decrease exhaust emissions. It has been determined that engine performance of a magnet placed in the fuel line is the highest in copper oxide added to diesel fuel [21]. Muthusamy et al. experimentally studied the addition of 20% Pongamia methyl ester and 50 ppm and 100 ppm iron oxide nanoparticles to diesel fuel in a diesel engine. Iron oxide nanoparticles added with biodiesel to diesel fuel especially increased thermal efficiency and reduced fuel consumption. HC and CO emissions decreased and NO_x emissions increased with iron oxide nanoparticles [22]. Kumar et al. experimentally studied three different rates of Pongamia biodiesel and three different rates of iron oxide added to diesel fuel in a diesel engine at four different load conditions. The addition of 20% Pongamia biodiesel to diesel fuel is the ideal mixture, and the addition of iron oxide has improved engine performance and exhaust emissions [23]. Kamesh and Madhu carried out experiments for different injection pressures in a diesel engine by adding 80 ppm and 100 ppm aluminum oxide, 100 ppm and 200 ppm iron oxide, and 80 ppm and 100 ppm zinc oxide to diesel fuel. Zinc oxide nanoparticles have achieved the greatest reduction in CO, and HC emissions. There was an increase in CO_2 emission with all nanoparticles [24]. Seela et al. experimentally studied the addition of biodiesel obtained from Mahua oil at three different rates and the addition of zinc oxide at two different rates to diesel fuel in a diesel engine at five different load conditions. Estimation of experimental data has been tried with generalized regression neural network. The addition of 20% biodiesel to diesel fuel is the most ideal mixture and the addition of 50 ppm zinc oxide has improved engine performance and exhaust emissions. They also suggested that since the generalized regression neural network model estimation is close to the experimental results, it can be used in future studies [25]. Nanthgapol et al. experimentally studied a mixture of 93% *Calophyllum inophyllum* methyl ester, 2% surfactant, and 50 ppm and 100 ppm zinc oxide and titanium oxide nanoparticles dissolved in 5% purified water in a diesel engine. *Calophyllum inophyllum* methyl ester caused a decrease in thermal efficiency and an increase in fuel consumption compared with diesel fuel. Despite the increase in thermal efficiency and decrease in fuel consumption with nanoparticles added to *Calophyllum inophyllum* methyl ester, it gave lower performance compared to diesel fuel. *Calophyllum inophyllum* methyl ester has improved in terms of emissions, apart from NOx emission, compared to diesel. Especially with the addition of titanium oxide 100 ppm, the best improvement in emissions, thermal efficiency and fuel consumption has been achieved [26]. D'silva et al. added titanium oxide with 80 mg/l solution to diesel fuel and tested fuel mixture in a diesel engine for five different loads. They found that with the addition of titanium oxide, 22% reduction in brake specific fuel consumption at full load, 18% reduction in unburned hydrocarbons and 25% reduction in carbon monoxide emissions compared to diesel fuel [27]. Sundararajan and Ammal experimentally tested 100% commercial diesel, 100% biodiesel from plastic waste, 93% commercial diesel and biodiesel from plastic waste, and 20 ppm, 40 ppm and 60 ppm titanium oxide nanoparticles dissolved in 5% purified water and 2% surfactant mixture effects on engine performance and emissions in a diesel engine. Biodiesel caused a decrease in thermal efficiency and an increase in fuel consumption compared to diesel fuel. Despite the increase in thermal efficiency and decrease in fuel consumption with titanium oxide nanoparticles added to biodiesel, it remained lower than diesel fuel. Titanium oxide adding to diesel fuel resulted in better engine performance and emissions compared to biodiesel mixture [28]. Örs et al. investigated the effects of the addition of biodiesel n-butanol and titanium oxide to diesel fuel on engine performance and emissions at full load in a diesel engine. The best improvement in engine performance was achieved with the addition of 80% diesel, 20% biodiesel and titanium oxide. The best improvement was obtained with 100% biodiesel and the second with 80% diesel, 20% biodiesel and titanium oxide [29]. Hasannuddin et al. investigated the effects of nanoparticles on fuel properties, engine performance and emissions by adding 50 ppm aluminium oxide, copper oxide, magnesium oxide, manganese oxide and zinc oxide to 10% pure water, 89% commercial diesel and 1% surfactant. They revealed that aluminium oxide, among the nanoparticles added to the fuel, gave the best performance [30]. In this study, the authors conducted an optimization study for the production of biodiesel and the use of biodiesel in internal combustion engines. In the study they obtained, they reported that the optimization techniques were successful in biodiesel production efficiency and engine tests [31]. In this study, the researchers tried to predict the effects of biodiesel production with CaO-doped catalyst and the use of biodiesel produced in diesel engine with artificial neural networks. They reported that a CaO-doped catalyst affects biodiesel production efficiency and increases production efficiency [32]. In studies, it is reported that the addition of nanoparticles to fuels increases combustion performance and is effective in reducing exhaust gas emissions. From this point of view, many of the various metallic additives are enriched by adding them to gasoline and diesel fuels [33]. In recent years, studies have been increasing that the addition of nanoparticles to diesel fuels has a positive effect on the combustion efficiency of fuels. In these studies, it is generally desired to increase the combustion surfaces of fuels and it is aimed to improve the fuel properties. For this purpose, it is observed that an excess of oxygen levels in the preferred fuels is more effective in achieving more positive results in combustion parameters [34–37].

Borax decahydrate ($Na_2B_4O_7 \cdot 10H_2O$) is named sodium tetraborate decahydrate and includes the elements of boron, sodium, hydrogen, and oxygen elements. Thanks to its high oxygen level, it is advantageous to use in many areas such as electrochemistry, energy, wood science, microbiology etc. [38–41]. High oxygen content significantly reduced unburned hydrocarbon, carbon monoxide and smoke density levels and increased CO_2 and NO_x emissions [42,43].

This study was carried out considering that the cost of nanoparticles generally used in the literature is very high. The cost of borax pentahydrate is more affordable than other nanoparticles. In this study, it was tried to examine the effects of oxygen-rich fuel mixtures on engine performance and exhaust gas emission parameters by adding oxygen-rich fuel mixtures to diesel fuel. For this reason, borax decahydrate was dissolved in methanol and mixed into diesel fuel as a fuel additive. The resulting mixture is used in a compression ignition engine, engine performance, combustion and exhaust emission data are examined in detail in the discussion section.

2. Materials and methods

2.1. Test fuels

The methanol used as a solvent of the solutions prepared in the experiment has Cas number of 67–56-1. The formula of borax decahydrate (Disodium tetraborate decahydrate) used as a solute is $Na_2B_4O_7 \cdot 10H_2O$ and has Cas number of 1303–96-4 and was obtained from Eti Maden İşletmeleri in Turkey. During the preparation of the solutions, Denver Instrument SI-234 branded device was used for weighing and Isolab I.613.01.001 branded magnetic stirrer was used for mixing of the solutions. During the preparation of the samples, firstly, the proportion of borax decahydrate to be added to the methanol was determined. The amount of borax decahydrate was determined at the rates of 0%, 1%, 3% and 5% according to the amount of methanol. In total, four samples were prepared. To dissolve the samples in methanol, the solutions were kept for 24 h at 550 rpm, 40 °C, via a magnetic stirrer. Since the obtained clear solution may contain impurities from the environment, it was filtered through Whatman No: 1 filter paper and obtained without insoluble particles solution.

Obtained borax decahydrate methanol mixtures were added to diesel fuel at a rate of 10% by volume. 100% diesel fuel D100M0, 10% pure methanol addition D90M10, 5 g borax decahydrate added methanol addition D90M10B1, 15 g borax decahydrate addition D90M10B2 and

Table 1
Physical and chemical properties of diesel and methanol.

Fuel Properties	Diesel	Methanol
Kinematics viscosity (mm^2/s), at 40 °C	3.4	0.59
Density (g/cm^3) at 15 °C	0.834	0.79
Lower heating value (kJ/kg)	43,010	20,300
Flash point (°C)	66	11
Cetan number	59.5	12
Oxygen (%, w)	0	50%

25 g borax addition D90M10B3 in the graphs of test results. Some physical and chemical properties of fuel mixtures are given in Table 1Table 2.

2.2. Experimental Setup and methodology

A naturally aspirated, four-stroke, air-cooled, direct injection, single-cylinder compression-ignition engine was used in the experimental study. The main characteristics of the diesel engine and generator used in this study are shown in Table 3.

Diesel engine was operated at a constant engine speed of 3000 rpm for all engine experiments. Each fuel mixture was operated at this engine speed at different brake loads (1000 W, 1500 W, 2000 W, 2500 W, 3000 W, 3500 W, and 4000 W). The schematic view of engine test setup is given in Fig. 1.

Fuel consumption was determined in mass with the time taken for 10 g of fuel to be consumed on an electronic balance with 0.01 g precision. In-cylinder pressure value was measured with Piezo resistor Kistler 4065B0200DS1 air-cooled pressure sensor. A charge amplifier (Kistler 4624AK21) was used to amplify the signals from the in-cylinder pressure sensor. Oprant AutoPSI-A model air-cooled pressure sensor was used to measure the fuel line pressure. The crankshaft position is determined by the FNC 50B incremental optical encoder.

A 4-channel PicoScope 2406B oscilloscope was used to monitor and record the data coming from sensors instantly. Each in-cylinder pressure and fuel line pressure value were obtained by averaging 100 cycles with 0.5 CA precision. Again, heat release analysis was carried out by using the average value of 100 consecutive in-cylinder pressures. All losses and leaks are ignored while calculating heat release rate. Heat release rate for each crank angle was calculated with Eq. (1).

$$\frac{dQ}{d\varnothing}=\frac{k}{k-1}\left(P\frac{dV}{d\varnothing}\right)+\frac{1}{k-1}\left(V\frac{dP}{d\varnothing}\right) \tag{1}$$

Where, $dQ/d\varnothing$ is heat release rate (J/CA), k is the ratio of specific heats (C_p/C_v), P is the cylinder pressure (Pa), and V is the variable cylinder volume (m^3).

Exhaust gas temperature was measured using a K-type thermocouple. Exhaust gas concentration of unburned HC, CO, CO_2 and smoke emission concentrations were determined by **Mobydic 5000 COMBI** exhaust gas analyser. The technical specifications of the exhaust emission device are presented in Table 4.

The total uncertainties of the measurements performed in the experimental study were calculated according to the Kline and McClintock method [44] Accuracy of measurements and total uncertainties are given in Table 5.

3. Experimental results

This study investigates effects of borax decahydrate and methanol mixture added to diesel fuel and exhaust gas emission values (CO, CO_2, NO_x, HC and smoke emissions) and in-cylinder combustion parameters (pressure-volume diagram (P–V), heat release rate (HRR), and ignition time) values.

Table 2
Some properties of test fuels and blends.

Properties	D90M10	D90M10B1	D90M10B2	D90M10B3
Kinematics viscosity (mm^2/s), at 40 °C	3.12	3.22	3.38	4.12
Density (g/cm^3) at 15 °C	0.83	0.84	0.86	0.89
Lower heating value (kJ/kg)	40,750	40,837	40,916	41,216
Flash point (°C)	60	65	68	75

Table 3
Test engine technical specifications.

Engine	Four strokes, direct injection, air-cooled and naturally aspirated
Model	186 FAG
Number of cylinder	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 (Before top dead center)

3.1. Structural characterizations

3.1.1. Fourier transform infrared (FTIR)- attitudes toward research (ATR) results

The Fourier Transform Infrared (FTIR) graphs show vibration types of chemical bonds of M10B1, M10B2, and M10B3 samples given in Fig. 2. According to the FTIR results, the vibrations of O–H stretching and CH_3 asymmetric stretching were determined the peak range at 3370-2950 cm^{-1} [45]. Also, this broadband occurring at 3370-2950 cm^{-1} was observed in all graphs and this band belongs to the O–H stretching vibration, which is one of the hydroxyl groups forming complexes with borate ions [46]. The peak values at 2860, 1467, 989, and 865 cm^{-1} showed the vibration of B–O stretching; the peak values at 1426 and 1330 cm^{-1} showed the asymmetric stretching of B–O in trigonal BO_3 bond type [47,48]. The peak value at 1700 cm^{-1} showed the vibration of C–H stretching [49]. The vibrations of C–O stretching were seen at 1229, 1057 cm^{-1} peak values [50]. The peak values at 773 and 699 cm^{-1} were assigned to bending vibrations of various borate bonds [51]. According to these results, chemical bond types of methanol and borax decahydrate were observed, but only Na bonds were not in Fig. 2. Because the bonds with sodium cannot be shown in FTIR results. For this reason, the sodium element was determined by the scanning electron microscopy (SEM-EDX) technique.

3.1.2. SEM-EDX results

SEM images of borax decahydrate powder were given in Fig. 3 as 50x (a) and 1000x (b) magnifications. When SEM images were examined, agglomerated structures were detected together with layered crystal structures. Since borax contains a high percentage of boron structures, it is natural to see agglomerated structures [52]. In the SEM images, it was seen that the borax used in the preparation of the samples was in micro dimensions.

Light elements with an atomic number less than 11 cannot be analyzed with EDS [53]. Since the atomic number of boron is 5, it could not be detected in the EDS measurement. The elemental concentration and other needed values were given in Table 6. In the EDS analysis, the element Sodium, which FTIR could not detect, was observed, and the peaks belonging to oxygen were also included. The oxygen concentration of the borax decahydrate sample was 69%. In other words, it is estimated that CO_2 emission increased, and CO emission decreased due to high oxygen concentration of the borax decahydrate sample.

3.2. Engine performance and combustion

3.2.1. Indicator diagram (P–V diagram)

Fig. 4 shows the P–V diagram at different engine braking loads. It has been observed that the in-cylinder pressure profile of the addition of borax decahydrate-added methanol to diesel fuel has a similar profile with diesel fuel. It has been observed that methanol borax decahydrate mixtures added to diesel fuel increase the maximum in-cylinder pressure and affect the combustion duration. The maximum in-cylinder pressure

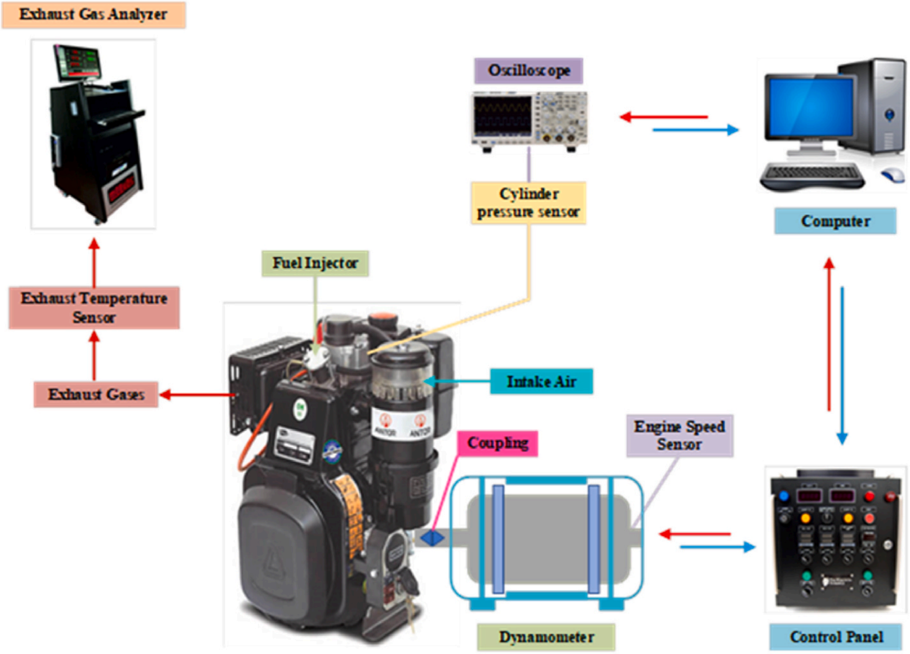

Fig. 1. Experimental setup.

Table 4
Technical properties of the devices used to measure exhaust emissions.

Measurement	Measuring Range	Precision
CO (% vol)	0–10	±0.06%
NOx (ppm)	0–5000	±5%
CO_2 (% vol)	0–20	±0.5%
HC (ppm)	0–20000	±12
Smoke opacity (%)	0–20	±1

Table 5
Measurement accuracies and uncertainties in the calculated results.

Measurement	Measuring Range	Accuracy (%)
Engine speed	Incremental encoder, rpm	±0.06
Cylinder pressure	Pressure sensor, bar	±0.05
Fuel mass	Precision scale, g	±0.1
Exhaust gas temperture	Thermocouple, °C	±1
Time measurement	Digital chronometer, s	±1
Calculated results	Uncertainty value (%)	
Power	±1.17	
BSFC	±1.54	

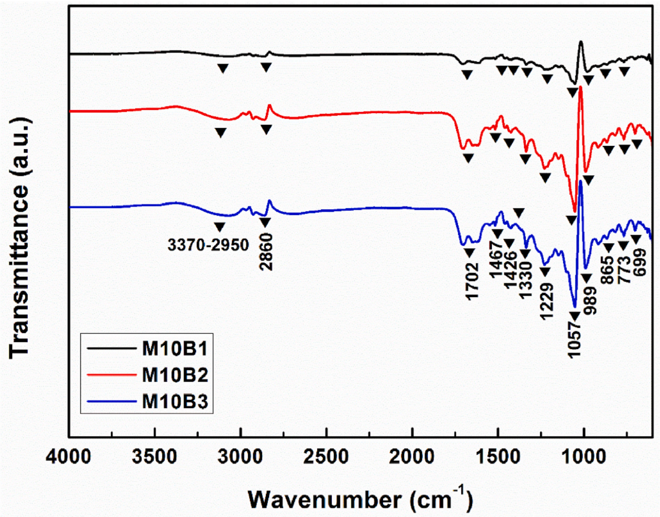

Fig. 2. The FTIR graphs of M10B1, M10B2, and M10B3 samples.

value was obtained with D90M10B3 fuel mixture at a brake load of 4000 W in all fuel mixtures. At this brake load, in-cylinder pressure value reaches its maximum value after 6 crankshaft angles (°CA) after top dead center (ATDC) with D100M0 fuel, while it reaches 5 °CA ATDC, D90M10B1 6 °CA ATDC, D90M10B2 7 °CA ATDC and D90M10B3 and 10 oCA ATDC values with D90M10 reached the maximum pressure values. In this case, it was determined that the combustion time was partially extended with the addition of methanol decahydrate. Studies on diesel engines report that the best fuel economy and maximum in-cylinder pressure values can be obtained if combustion occurs 6–10 °CA after TDC [54]. The results obtained show that the maximum pressure value is within limits in literature with the addition of borax decahydrate methanol mixture for diesel engines.

In recent years, it has been mentioned that nanoparticle materials added to fuels are effective on internal combustion engine combustion parameters [55]. It has also been observed that especially oxygen-rich nanoparticles are preferred more and positive results are obtained [56,57]. Borax decahydrate is known as a compound containing high oxygen, hydrogen, and carbon due to its structure. It should be considered that hydrogen, oxygen, and carbon bonds, which will tend to burn when dissolved in methanol, may be released. For this reason, combustion efficiency has increased and an increase in in-cylinder pressure values has been observed. Studies on nanoparticles mention different reaction mechanisms [58]. In diesel engines, combustion takes place by injecting the fuel into the cylinder by an injector. In this case, the fuel beam is at micron levels. Many studies state that nanoparticles added to the fuel beam create an ideal fuel/air mixture by creating an explosion effect during combustion [59]. In such cases, it can be mentioned that it increases combustion efficiency by exhibiting better performance. It is mentioned that some nanoparticles mix well with fuel mixtures, bond easily with hydrogen and carbon bonds, and increase the combustion surface, thus increasing the in-cylinder pressure values [60].

The effect of different brake loads and fuel mixtures on in-cylinder pressure changes are given in Fig. 5. All cases outlined above for

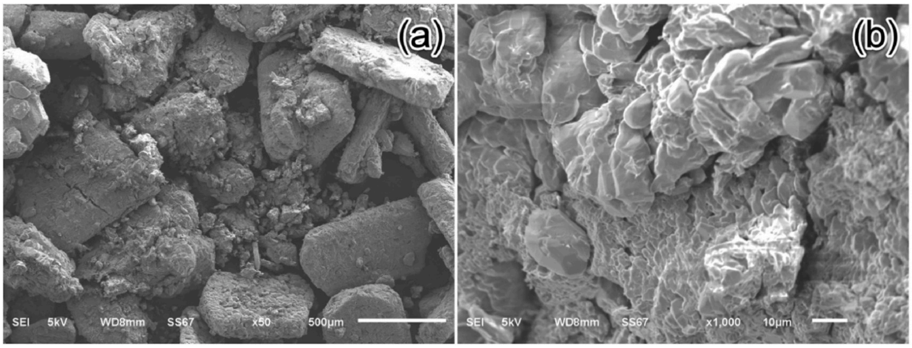

Fig. 3. Sem images of borax decahydrate powder: Magnification as (a) 50x, (b) 1000x.

Table 6
The elemental analysis of borax decahydrate sample with EDS measurement.

Elt.	Line	Intensity (c/s)	Error 2-sig	Conc	Units	
H	Ka	0.00	0.000	0.000	wt.%	
B	Ka	2.95	0.791	0.000	wt.%	
O	Ka	515.48	5.904	69.165	wt.%	
Na	Ka	203.73	3.785	30.835	wt.%	
				100.000	wt.%	Total

nanoparticle addition with borax decahydrate mixture dissolved in methanol showed a similar trend. It is thought that in-cylinder pressure values increase for these reasons [61]. A decrease was observed in the maximum in-cylinder pressure values with the D90M10 fuel mixture at all brake loads. Combustion performance of fuels in internal combustion engines: It changes depending on physical and chemical properties such as heating value, viscosity, density, heat of vaporization, and cetane number [62]. The heating value and the cetane number decrease with adding methanol to the diesel fuel in D90M10 fuel mixture. In addition, the heat of evaporation increases. Maximum in-cylinder pressure values have decreased since it creates negative results in terms of combustion performance. The in-cylinder pressure values increased using all fuel mixtures depending on the increase in brake load. Despite this, it is believed that the oxygen level in borax decahydrate affects the combustion and overcomes the negative decrease in thermal value. The literature mentions that oxygen-rich metal-doped fuels are added to diesel engine fuels with similar results [[63]][[64]]. The highest in-cylinder pressure increase rate was 6.8% with D90M10B3 fuel mixture at 1000 W brake load. The lowest increase rate among all brake loads using the D90M10B3 mixture was observed with a rate of 2.5% at 2500-W engine brake.

3.2.2. Heat release rate (HRR)

Fig. 6 shows changes in HRR at different brake loads. Heat release rate represents the variation of combustion in in-cylinder per ^{o}CA. HRR value calculated by accepting some assumptions in the laws of thermodynamics is significant in making sense of combustion time in an in-cylinder [65]. In general, combustion time is prolonged with nanoparticles addition to diesel fuel [66]. Nanoparticles have effects on the viscosity, density, calorific value and heat of vaporization of fuels. Excessive increase or decrease in these values affects combustion parameters. Studies have reported that HRR increases with oxygen-rich nanoparticle addition [67]. Studies have reported that fuels with the addition of nanoparticles create a micro explosion, resulting in a better combustion mixture and an increase in the amount of HRR in the cylinder [68]. In addition, carbon and hydrogen atoms in nanoparticle contents and combustion viscosity value significantly affect HRR increase. The lowest value in all HRR ratios was obtained with D90M10 fuel mixture, while the highest HRR value was obtained with D90M10B3 fuel mixture. The heating value decreases with methanol addition to diesel fuel. In this case, a decrease in HRR is expected. In addition, a significant increase in HRR is observed with nanoparticle addition.

3.2.3. Combustion time

Fig. 7 shows HRR graph of a diesel engine and explanations of combustion process. Ignition delay, premixed combustion and controlled combustion sections can be determined with some values accepted on the chart [69].

Fuel mixture's effects on combustion times at 4000 W brake load are given in Fig. 8. The time from injection of first fuel jet from injector of diesel engines to section where the first combustion takes place is called the ignition delay (ID). This section may vary with fuel mixtures values such as cetane number, heat of vaporization, viscosity and density [70,71]. ID time shorten with borax decahydrate methanol mixture addition to diesel fuel. It is also possible to express this situation as combustion occurs in a shorter time. Studies have reported that it is possible for fuel particles sprayed with air/fuel mixture in an in-cylinder to evaporate and create ideal conditions for combustion to take place in a shorter time [72]. In this study, it is possible to mention that the oxygen-rich content of additive partially shortens combustion. It is known that methanol and borax decahydrate dissolved in methanol contains high levels of oxygen. It is thought that the combustion may have started partly earlier, as oxygen causes easier oxidation. On the other hand, viscosity, density and heat of vaporization increase with D90M10B3 fuel mixture. Since such a fuel mixture cannot provide an ideal air/fuel ratio, there may have been prolonged re-burning times. While there is almost no change in the premixing phase with methanol addition to diesel fuel, a shortening is observed in the premixing phase with borax decahydrate. It has been determined that total combustion time is shortened the most with D90M10B2 fuel mixture. The results of the study are similar to studies containing nanoparticles in the literature [73].

3.3. Break specific fuel consumption

Variation of break specific fuel consumption (BSFC) value at different brake loads is given in Fig. 9. BSFC is accepted as an important criterion in planning commercial use of fuel in studies with alternative fuels. BSFC describes fuel amount needed to do one kW of work for an hour [74]. The results obtained show that the lowest fuel consumption value is the highest in addition to borax decahydrate. It is believed that with the addition of borax decahydrate, which is rich in oxygen, the combustion efficiency in the cylinder increases and, in this case, reduces the fuel consumption value. In studies conducted on the addition of nanoparticles, it is reported that oxygen-rich fuels change the combustion time and partially improve the combustion in the cylinder, reducing the amount of BSFC [[36]][[75]]. Studies indicate that BSFC depends on the properties of fuels, such as heating value, viscosity, density and cetane number, and the oxygen content of fuels [76,77]. The lowest BSFC was determined with D90M10B3 fuel mixture and the highest BSFC was determined with D90M10 fuel mixture at all brake loads.

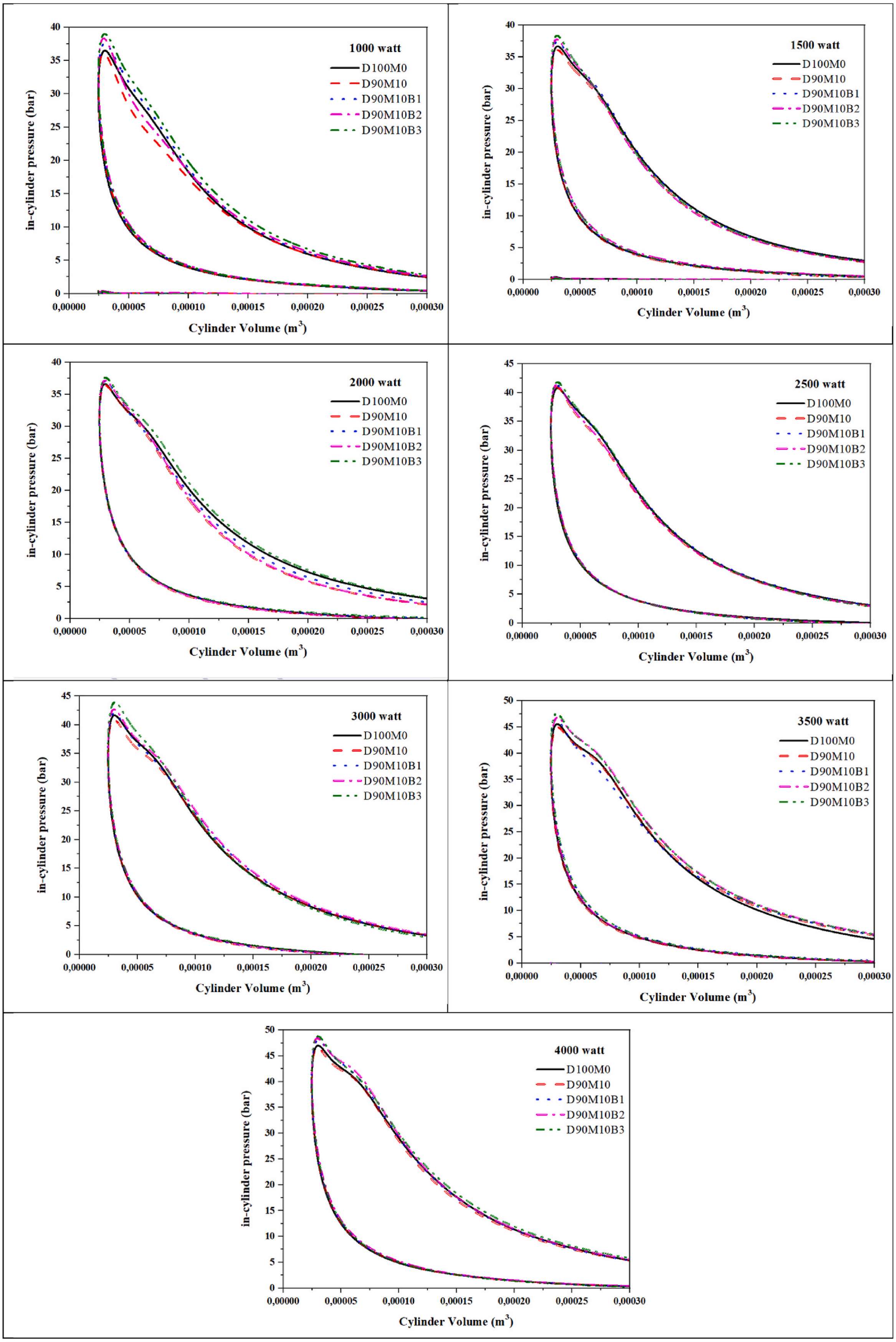

Fig. 4. Effect of different fuel mixtures and brake loads on the *P*–V diagram.

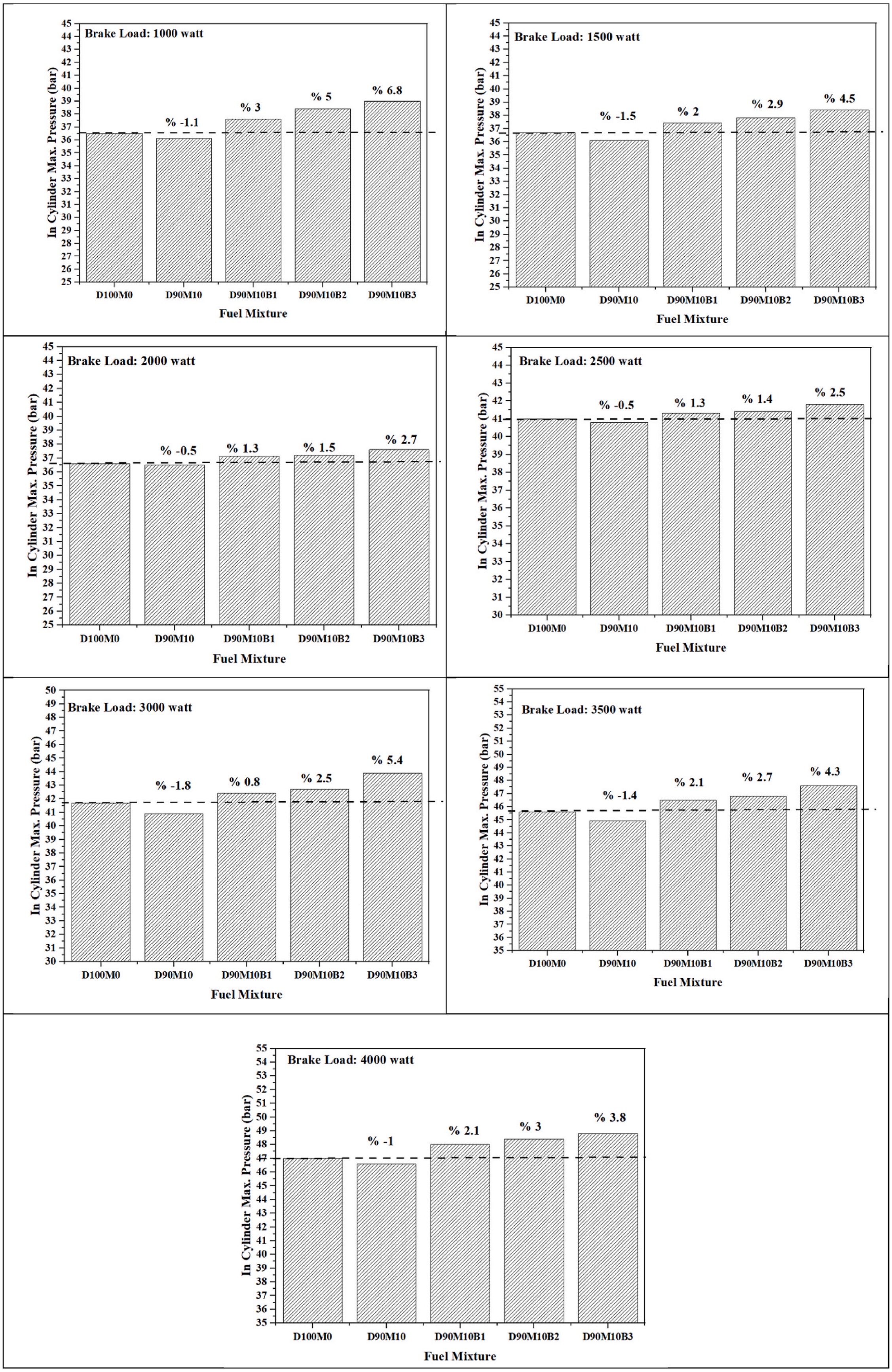

Fig. 5. Effect of different fuel mixtures on the maximum in-cylinder pressure changes under different brake loads.

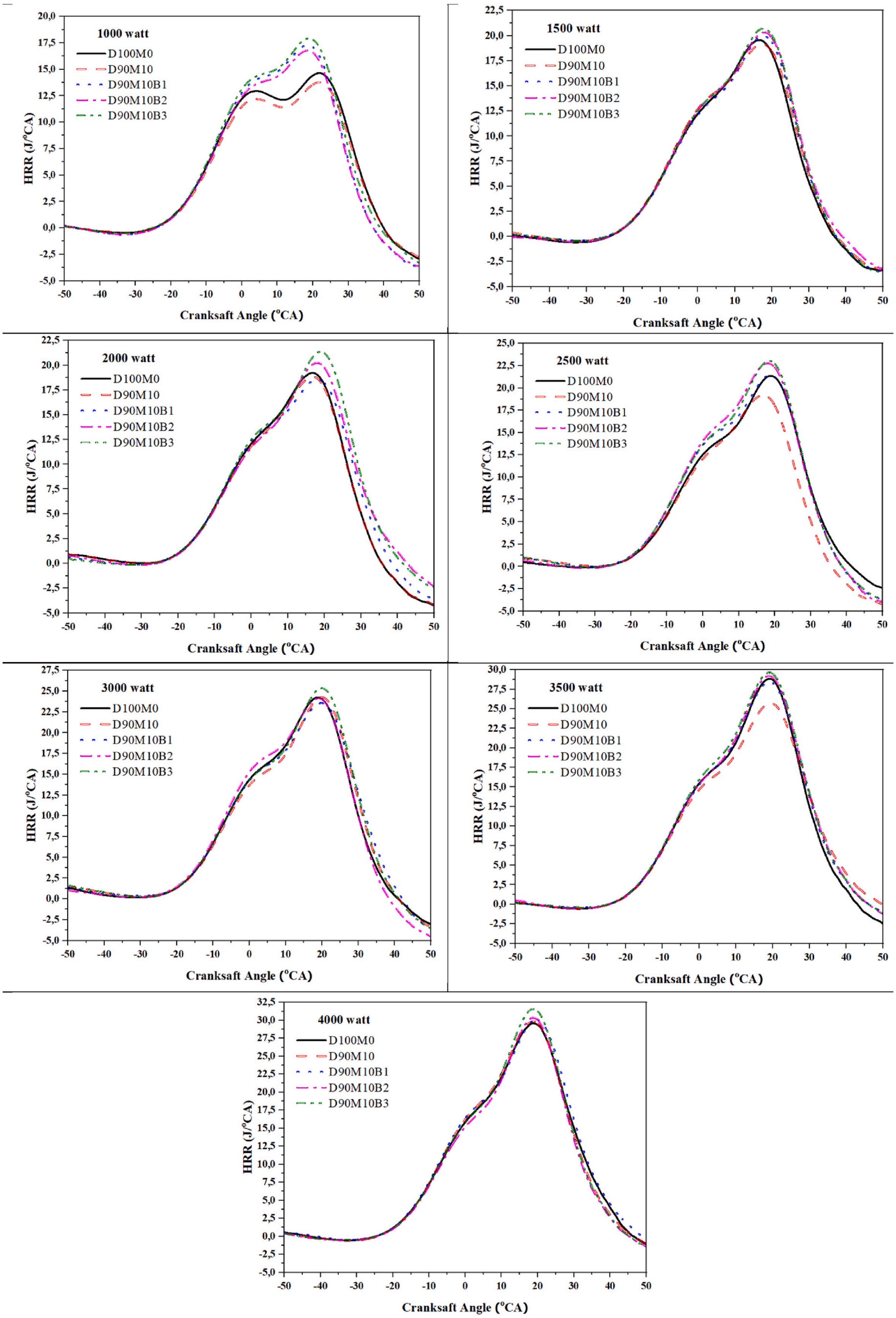

Fig. 6. HRR effect of different fuel mixtures and brake loads.

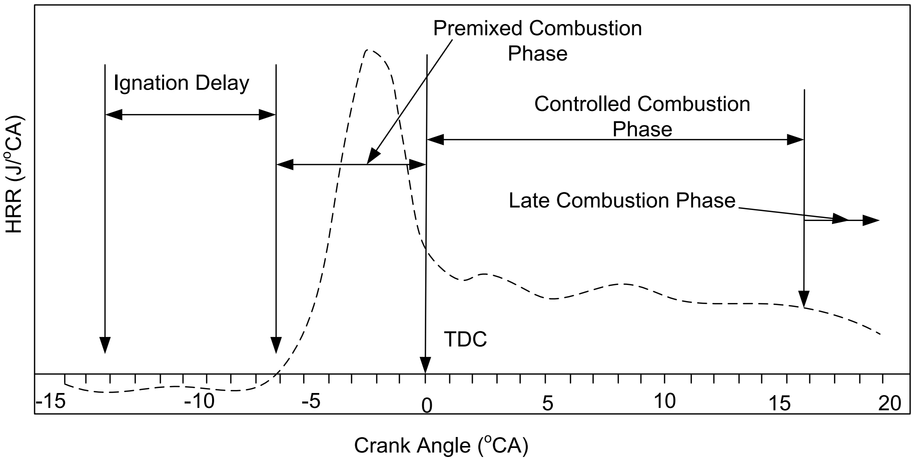

Fig. 7. Details of heat release rate.

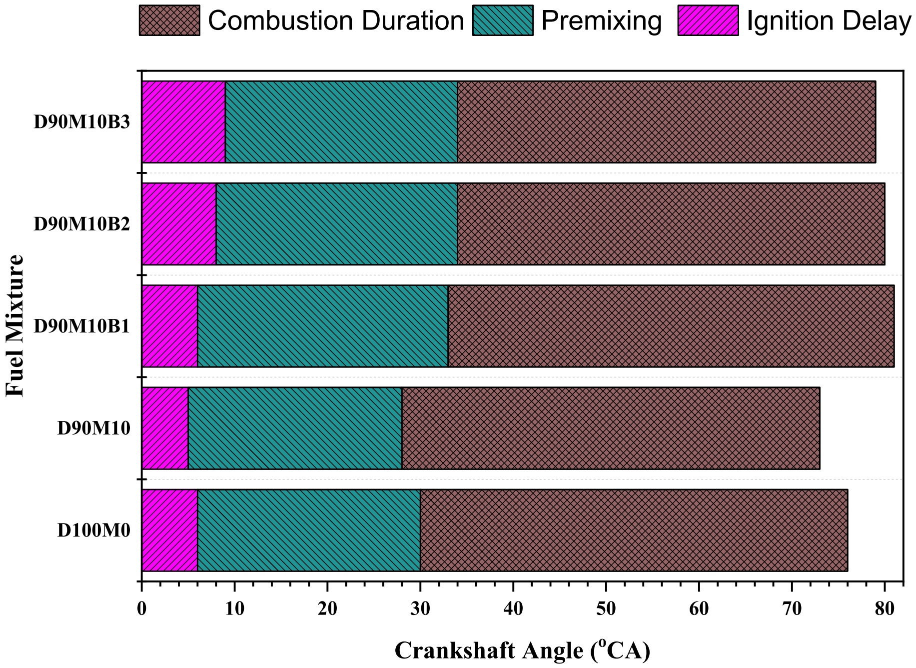

Fig. 8. Effect of different fuel mixtures on combustion times at 4000 W brake load.

3.4. *CO emission*

The variation of CO emissions at different brake loads is given in Fig. 10. CO emissions occur because of partially unburned fuels being discharged from exhaust due to cold regions in a cylinder. The basic phenomenon for CO emissions is oxygen (O_2) deficiency. Diesel engines work with a large amount of air. For this reason, CO emissions occur less than gasoline engines. However, it is possible to explain CO formations in diesel engines with oxygen deficiency. Sometimes air/fuel mixtures do not mix well, and sometimes incomplete combustion areas can be formed by the partial collision of the fuel with cold regions [78]. CO emissions may increase in such cases. In this study, there is not an increasing situation, on the contrary, there is a decreasing situation. There is a decrease in CO emissions at all brake loads with the addition of methanol and methanol borax decahydrate mixture to diesel. This decrease thought that due to the amount of oxygen in the methanol and methanol borax decahydrate mixture addition to diesel fuel. In addition, it can be stated that nanoparticles create a micro-explosion during spraying, creating a better air/fuel mixture ratio, partially improving combustion and reducing CO emissions. In studies with nanoparticles [79,80], it is mentioned that the micro-explosion phenomenon causes the improvement of air/fuel mixtures. Thus, combustion efficiency is partially increased and affects emissions. The addition of oxygen-rich nanoparticle fuels to diesel fuels is reported to reduce CO emissions. The common opinion in the studies is that oxygen oxidizes carbon atoms in the cylinder and partially improves combustion [81]. While CO emission was measured as 0.11 ppm with the D100M0 fuel mixture at 4000 W brake load, it was measured as 0.05 ppm with D90M10B3 fuel mixture under the same conditions.

3.5. *CO_2 emission*

Fig. 11 gives the variation of CO_2 emissions at different brake loads. CO_2 emissions are expressed as complete combustion fuel products in internal combustion engines. CO_2 emissions can also be expressed as an indicator of combustion. In studies involving the addition of nanoparticles to diesel fuel, the researchers explain combustion efficiency with the following points. These can be expressed as increasing oxygen

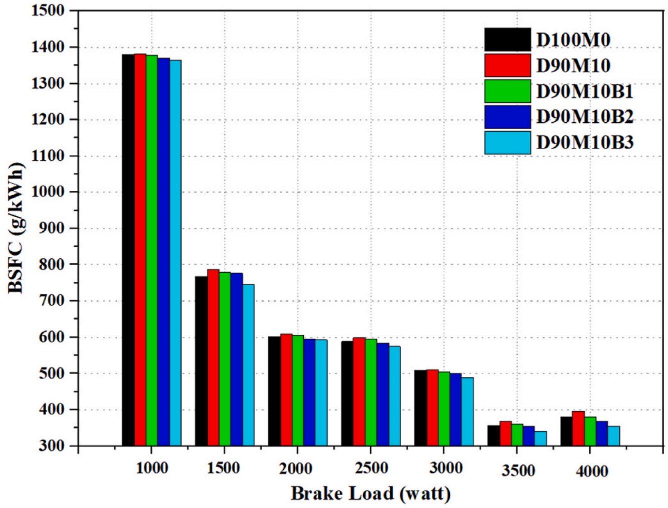

Fig. 9. Specific fuel consumption variation for different loads.

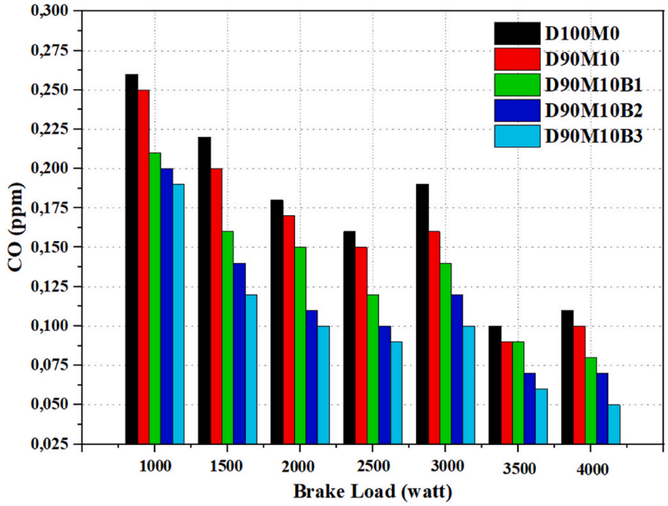

Fig. 10. CO variation for different loads.

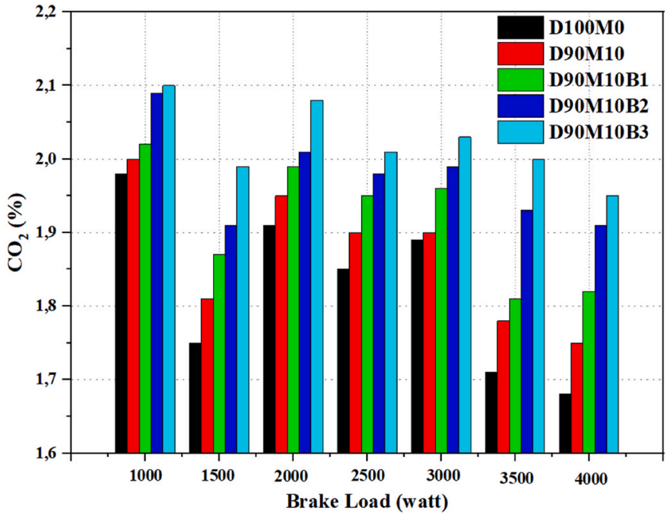

Fig. 11. CO_2 variation for different loads.

content [59,82,83], changing C/H ratio [84], micro explosion [85,86] and increasing combustion surface area [87–89]. With the addition of borax decahydrate to diesel fuel, the amount of oxygen in the fuel mixture increases. It is observed that this situation reduces CO emissions, which are the product of incomplete combustion, and increases CO_2 emissions, which are the product of complete combustion. In the literature, it is reported that using oxygen-rich nanoparticle addition as a fuel additive is effective in forming similar results [90]. In some studies, it is possible to see that CO_2 emissions decrease with the addition of nanoparticles. It is generally possible to come across studies that report that the addition of metal-reinforced nanoparticles partially worsens combustion and that CO_2 emissions tend to decrease [91]. In these studies, researchers attribute the worsening of combustion to the change in combustion time, an increase in fuel mixtures' viscosity and density values [92]. This study showed an increase in CO_2 emissions compared to diesel fuel at all brake loads. The highest increase rate was obtained in D90M10B3 fuel mixture. In addition, the tendency to decrease over CO emissions also reveals the accuracy of CO_2 emission results.

3.6. HC emission

Variation of HC emissions at different brake loads is given in Fig. 12. HC emissions occur in internal combustion engines when there are rich mixing zones [93]. This is usually result of oxygen lack. Sometimes, HC emissions can occur rapidly with the partial flame extinction of fuel reaching cold walls in-cylinder [94]. HC emissions tend to decrease with mixture of methanol and methanol borax decahydrate to diesel fuel. The best reduction in HC emissions was obtained with D90M10B3 fuel mixture. The oxygen ratio in methanol and methanol borax decahydrate mixture affects combustion efficiency by partially increasing combustion performance. For this reason, it is thought that HC emissions are reduced. Similar studies are frequently mentioned in literature [95]. In studies examining the effects of nanoparticle addition to diesel fuel, it is mentioned that the C/H ratio changes and this situation changes HC emissions [96]. With the addition of methanol and methanol borax decahydrate to diesel fuel, HC emissions are expected to decrease as C/H ratio tends to decrease. In addition, when similar studies in the literature are examined, it is seen that the addition of nanoparticles changes HC emissions in the event that the air/fuel ratios of fuel mixtures change [73]. The results of the study are like all studies in the literature that contain nanoparticle addition with rich oxygen content [97]. HC emission values were measured 75 ppm for D100M0 fuel mixture, 70 ppm for D90M10 fuel mixture, 64 ppm for D90M10B1, 60 ppm for D90M10B2

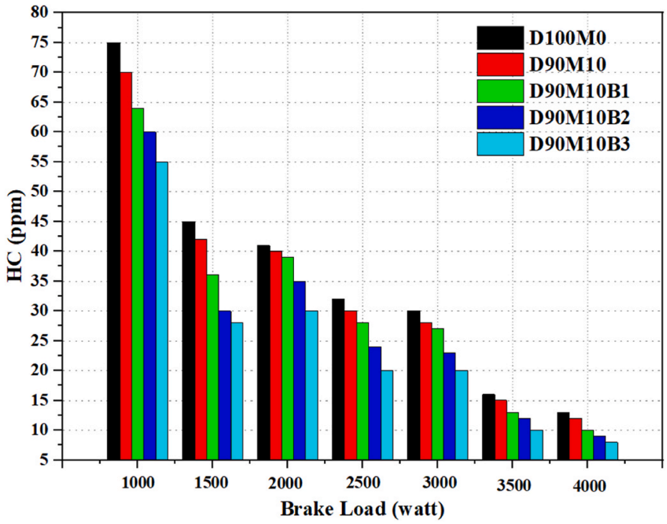

Fig. 12. HC variation for different loads.

and 55 ppm for D90M10B3 fuel mixture at 1000 W brake load under the same conditions.

3.7. Exhaust gas temperature

Fig. 13 gives exhaust gas temperature variation at different brake loads. Exhaust gas temperature is accepted as an indicator of combustion in-cylinder for internal combustion engines. For this reason, it is known that the effects of combustion in-cylinder will cause an increase or decrease in exhaust gas temperature [98]. In particular, studies report that the exhaust gas temperature increases with using oxygen-rich fuels [99]. An increase in exhaust gas temperature was observed with methanol and methanol borax decahydrate mixtures added to diesel fuel. With the addition of methanol, more fuel is sent into the cylinder. This means a greater increase in energy in-cylinder. In this case, exhaust gas temperature increased with the addition of the oxygen factor in fuel. Similar results are reported in studies with methanol. In general, it is reported that the changing combustion timing with the use of nanoparticle fuel additives added to diesel fuels influences exhaust gas temperatures [100,101]. The highest exhaust gas temperature was obtained with D90M10B3 fuel mixture at all brake loads. While exhaust gas temperature value of 568 °C was obtained with D90M10B3 fuel mixture 4000 W brake load, exhaust gas temperature value of 537 °C was measured with D100M0 fuel mixture under the same conditions.

3.8. NO_x emission

Fig. 14 shows the variation of NO_x emissions at different brake loads. High-temperature zones are formed by forming a rich mixture of fuel sprayed into air taken into the cylinder. At these high temperatures, nitrogen oxide emissions occur with the reaction of O_2 and N_2 in the air. Studies have reported that factors such as the combustion duration, the maximum temperature in the combustion chamber, the residence time at the maximum temperature, and the composition of the burned fuels effectively form NO_x emissions [61]. In studies where nanoparticles are added to diesel fuels as additives, it is reported that nanoparticles cause micro-explosion and partially improve combustion [101]. In studies investigating the mechanisms of nitrogen oxide formation, it is stated that nitrogen oxides show an increase in reactions with sudden combustion [102]. As stated in Fig. 10, exhaust gas temperatures tended to increase when methanol added borax decahydrate was added to diesel fuel. In this case, an increase in NO_x emissions emerges as an expected situation. It is possible to explain this situation by the increased amount of oxygen in the fuel, the microburst property of borax decahydrate and the change in combustion time. The results obtained are similar to the studies in the literature [103]. While the highest NO_x emission value was obtained as 236 ppm with D90M10B3 at 4000 W brake load. NO_x emission was measured as 206 ppm with D100M0 fuel and 200 ppm with D90M10 fuel mixture under the same conditions.

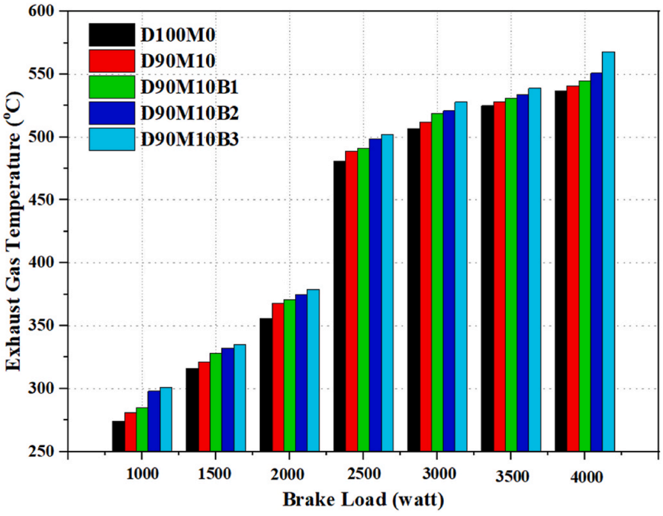

Fig. 13. Exhaust gas temperature variation for different loads.

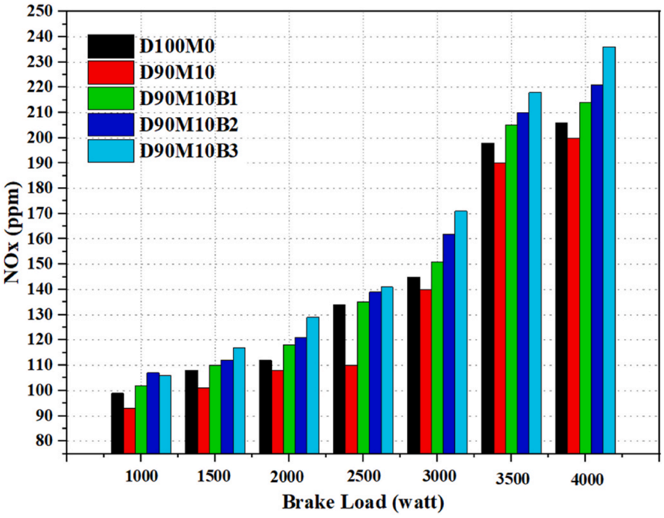

Fig. 14. NO_x variation for different loads.

3.9. Smoke opacity

Fig. 15 shows the variation in smoke opacity emissions at different brake loads. Smoke opacity emissions occur when fuels are ejected from exhaust without being partially combustion into the cylinder [104]. Studies show that smoke opacity emissions vary with parameters such as Air/Fuel (A/F) ratio in-cylinder, the calorific value of fuels, viscosity, density, and cetane number [105]. It is mentioned that combustion partially improves and reduces smoke opacity emissions by adding oxygen-rich fuels to diesel fuel [106,107]. In addition, using fuel mixtures containing nanoparticles, Smoke opacity emissions decreased with the addition of methanol and methanol borax to diesel fuel. The results of the study show similarities with the effects of oxygen-containing nanoparticle fuel additives in the literature [108,109]. This can be explained by the oxygen content of borax decahydrate added to diesel fuel. In addition, studies conducted on nanoparticles in the literature report that changes in viscosity, density and burning time have an effect

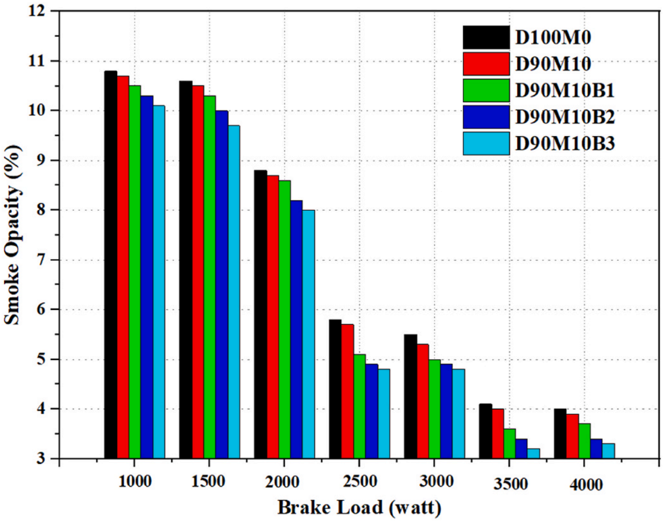

Fig. 15. Smoke opacity variation for different loads.

on smoke emissions [64, 110, 111]. The highest reduction amount was determined with D90M10B3 fuel mixtures. The presence of oxygen in methanol and borax decahydrate is thought to improve combustion partially and reduce smoke opacity emissions. While 4% smoke opacity emission value was measured in D100M0 fuel at 4000 W brake load, 3.3% smoke opacity emission value was measured with D90M10B3 fuel mixture under the same conditions.

4. Conclusion

Nanoparticles used as fuel additives in the literature are generally expensive materials. Adding it to commercially used fuels can cause serious increases in fuel prices. For this reason, borax decahydrate, which is more cost-effective and has more oxygen-rich content than other nanoparticles, was dissolved in methanol as nanoparticles and added to diesel fuel.

Dissolving borax decahydrate in methanol and adding it to diesel fuel caused an increase in maximum in-cylinder pressure value and a forward shift of crank angle formed. This can be explained by the oxygen content of borax decahydrate, the change in combustion timing and the effect on the air/fuel mixture. D90M10B3 fuel mixture, where the maximum in-cylinder pressure occurs, also gave maximum heat release rate value. Ignition delay was prolonged addition of borax decahydrate and combustion took place in a shorter time. Adding borax decahydrate increased CO_2 emission and reduced CO emission Due to combustion efficiency increasing. This improvement in combustion is understood as decreasing CO emissions and increasing CO_2 emissions. Exhaust gas temperature and NO_x emission increased with combustion improvement increased maximum temperature. All the results show that borax decahydrate can be used as a diesel fuel supplement and that it affects exhaust gas emissions and combustion parameters.

In this study, the amount of borax decahydrate that can be dissolved with a maximum of 500 ml of methanol is 25 gr. This means a 5% solution for methanol borax decahydrate mixture. By mixing solution with diesel fuel, a maximum of 0.5% could be added. For future studies, combustion efficiency can be increased with alcohol fuels in which borax decahydrate can be more soluble. Injection time or gradual spraying operation can be performed to prevent the increase of NO_x and exhaust gas temperature due to an increase in combustion temperature. In the future, it is important to increase the studies aimed at investigating the effect of long-term use of borax decahydrate in diesel fuel on materials in terms of using borax.

Credit author statement

Salih Özer: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.Usame Demir: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing.Serhat Koçyiğit: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability

The authors do not have permission to share data.

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