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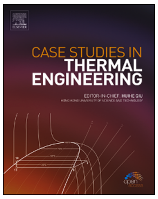

Energy, exergy and sustainability analyses of nanoparticles added to fuels to reduce carbon footprint

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ABSTRACT

In this study, experimental and thermodynamic analyses were used to investigate the use of fuel blends created by adding cerium oxide (CeO_2) and aluminium oxide (Al_2O_3) nanoparticles to diesel/heavy fuel oil (HFO) fuel blends in a compression ignition engine. In the study, a single-cylinder compression ignition engine was tested at four different engine loads at a constant engine speed of 3000 rpm. The experiments measured engine power, fuel consumption, exhaust gas temperature, engine casing temperature and exhaust pollutants. Thus, a study on energy, efficiency and sustainability was carried out by comparing fuel blends. All fuel blends were subjected to energy and exergy efficiency, lost exergy and sustainability index calculations. The addition of nanoparticles to the fuel increases the energy loss compared to the D80F20 (80% Diesel + 20% HFO) fuel blend. Comparing D80F20AL100 (80% Diesel + 20% HFO + 100 ppm Al_2O_3) and D80F20CE100 (80% Diesel + 20% HFO + 100 ppm CeO_2) fuel blends, the exergy loss of D80F20 fuel is 10.76% and 14.23% higher when the engine power is 4000 W, respectively. The energy efficiency of D80F20 fuel increases as more nanoparticles are added and reaches 12.60% and 12.80% for D80F20CE25 (80% Diesel + 20%HFO + 25 ppm CeO_2) and D80F20CE100 fuels under 3000 W engine load, respectively. The inclusion of nanoparticles in diesel/HFO fuel blends gives results in line with the sustainability index.

Nomenclature

HFO	Heavy Fuel Oil
CeO_2	Cerium Oxide
Al_2O_3	Aluminium Oxide
D80F20	80% Diesel +20% HFO
D80F20Al25	80% Diesel +20%HFO +25 ppm Al_2O_3
D80F20Al100	80% Diesel +20%HFO +100 ppm Al_2O_3
D80F20CE25	80% Diesel +20%HFO +25 ppm CeO_2
D80F20CE100	80% Diesel +20%HFO +100 ppm CeO_2

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n	Engine Speed
T	Engine Torque
$\dot{E}_{loss}$	Thermal Losses
$\dot{E}_f$	Fuel Energy
T_s	The Engine Body
CO	Carbon Monoxide
HC	Hydrocarbon
NOx	Nitrogen Oxide
ppm	Parts Per Million

1. Introduction

Fuel Oil is a petroleum derivative. Compared to other liquid fuels used in domestic and commercial heating, fuel oil has high calorific value, high viscosity, and high density. Fuel oil has different types depending on its chemical and physical properties. However, commercially it is usually referred to as HFO. According to research, fuel oil has a high mass percentage of carbon content. It also contains ash, water, sulphur, hydrogen, and small amounts of Sulphur [1]. According to international agreements, the sulphur content of HFO used should not be higher than 3.5% [2].

The use of HFO in ship engines has increased rapidly in recent years. Because the production cost of HFO is cheaper than diesel fuel. In addition, despite the discontinuation of the production of diesel-powered automobiles, diesel engines are still used in construction equipment requiring large power. Therefore, existing academic research on HFO has also started to increase. According to Özer and Doğan, energy and exergy analyses of HFO added to diesel fuel were performed. They stated that diesel fuel can contain up to 40% HFO and can be used in diesel engines [3].

Tariq and Saleh investigated the effects of blending 20% HFO with diesel fuel in a compression ignition engine. Firstly, they reduced the sulphur content of HFO by chemical treatment and increased the cetane number by adding additives. Then, they subjected the fuel mixture to heating to reduce the viscosity and density values. They reported that the fuel combination and heating method they obtained after all processes had an effect on exhaust emissions [4]. Anssi Järvinen et al. aimed to reduce the wastes produced by HFO by using a scrubbing system on an HFO-fuelled ship. For this reason, they focused on sulphur and black soot production related to the combustion of HFO. They reported that the study on the washing process was successful and the washed HFO caused less sulphur and soot formation [5].

Fan Zhang and others have looked at the results of using HFO in low-volume marine engines. According to the research that was done, the usage of HFO releases pollutants into the environment, including sulphur and ash [6]. In addition, there may be issues with its direct usage and decreased combustion efficiency due to the high viscosity and density values of HFO. This makes it possible to use such high-viscosity fuels by diluting them in certain ways.

On the other hand, papers on the impacts of incorporating nanoparticles into fuels have been published often in recent years. The effects of nanosized TiO_2 supplementation added to diesel/biodiesel fuel blends have been researched by Uslu and colleagues. It improves motor performance, according to their findings [7]. By incorporating ZnO nanoparticles of a certain size into biodiesel made from used vegetable oils, Vali and his colleagues were able to better understand the pressure variations within the cylinder. Their findings show that the performance characteristics of the engine are impacted by the addition of ZnO [8]. Özer et al. experimentally investigated the effects of adding borax decahydrate to diesel fuel. The researchers claim that the use of borax changes the combustion time and improves emissions [9]. Esanay and his colleagues added nanotubes at a level of 50 ppm to diesel fuel used as pilot fuel in a diesel engine and ran the engine with natural gas supplementation and then observed the results. According to the study, a diesel fuel combination containing nanoparticles produced better engine performance [10].

In this study, Uysal et al. investigated the effects of nanoparticle addition to fuel blends using exergy analysis. According to some studies in the literature, the addition of graphene oxides to diesel fuel increases the energy cost and improves the sustainability index. Therefore, it is important to investigate the nanoparticles added to fuels in terms of exergy analysis [11]. Haseeb and colleagues investigated the results of adding Fe_2O_3 nanoparticles to used tire pyrolysis oil. They claimed that the use of the mixtures they developed for this purpose increased engine efficiency, reduced fuel consumption and exhaust emissions. They also stated that the addition of Fe_2O_3 is sustainable in terms of both sustainability index and economic analysis as well as energy analysis [12].

In the research conducted by Uslu and Çelik [13], CeO_2 nanoparticles, a reactive additive, were added to diesel fuel at different rates. Adding nanoparticles reduced fuel consumption and increased exhaust temperature. The optimum operation of the engine is calculated as 100 ppm CeO_2 amount and 12 Nm engine. Catalytic combustion is recommended to eliminate soot from compression ignition engines. Combustion performance can be improved by using CeO_2 [14]. In addition, adding CeO_2 to diesel fuel reduces carbon monoxide (CO) and hydrocarbon (HC) emissions while causing an increase in nitrogen oxide (NOx) emissions [15,16]. If Mahua oil biofuel is used in a diesel engine, combustion properties can be improved by adding Al_2O_3 and CeO_2 nanoparticles. In the research conducted by Hameed and Muralidharan [17], brake specific fuel consumption decreased by approximately 3%, while thermal efficiency increased by approximately 1.5%.

Adding hydrogen to diesel/biodiesel fuel blends in compression ignition engines reduces fuel consumption and increases thermal efficiency [18]. Biodiesel damages injection systems in diesel engines due to its high viscosity. At the same time, fuel consumption increases since the lower calorific value of biodiesel is lower than diesel fuel. The use of hydrogen in diesel/biodiesel fuel blends positively affects combustion efficiency [19,20].

Studies on the use of alternative fuels to diesel engines continue in the literature. Renewable Densified Fuels (RDF) produced from waste in recent years will be environmentally beneficial [21]. Alophyllum inophyllum seed oil, which can be a fuel similar to diesel fuel, causes problems in use due to its high viscosity. However, the viscosity of this seed oil can be improved by using thermal catalytic technique at three consecutive different temperatures and can be used as an alternative to diesel fuel [22].

According to studies, nanoparticles added to motor fuels as additives have an impact on the combustion process and exhaust emissions. However, even though HFO is a cheap and practical fuel, there hasn't been much scholarly research done in this area. This study focuses on a subject that will help us fill a gap in the literature by offering a fresh viewpoint and combining HFO with nanoparticle addition in the sense of energy and exergy analysis.

When studies in the literature are examined, there are studies examining the effects of nanoparticles added as additives to diesel and biodiesel fuel blends on the combustion process and exhaust emissions. However, research on the combined use of HFO, a cheap and practical fuel, and nanoparticles is limited. This study aims to examine the data obtained from the performance and emission tests of HFO nanoparticles with thermodynamic analysis. With energy and exergy analysis, the effect of the nanoparticle added to HFO on thermal efficiency, exergy destruction and exergy efficiency is examined.

2. Materials and methods

The study was carried out in accordance with the flow chart given in Fig. 1. First, a dual fuel mixture of diesel fuel oil was provided. Triple fuel mixtures were obtained by adding Al_2O_3 and CeO_2 nanoparticles in different proportions to this dual fuel mixture. Performance and emission tests were carried out with these mixtures in diesel engines at different engine powers. Energy, exergy and sustainability analyzes were carried out using the data obtained from the tests.

2.1. Test fuels

The fuels used in the study were obtained from local companies engaged in commercial sales. Table 1 lists some properties of diesel fuel and HFO and Table 2 lists some properties of nanoparticles added to the fuel.

The HFO was heated to a temperature of 70 °C, passed through a coarse filter and then allowed to cool. The solid particles in the HFO fuel were removed by passing through a diesel filter. The filtered HFO was added to the diesel fuel at the rate of 20% by volume to form the D80F20 fuel combination. The resulting fuel blends were analyzed in an accredited laboratory (Table 3 and 4). The resulting D80F20 fuel mixture was then supplemented with Al_2O_3 and CeO_2 nanoparticles at 25 ppm and 100 ppm. The fuel blends were mechanically stirred for 2 h after the nanoparticles were added. When processing the experimental fuels, the fuels that passed through all these procedures were subjected to re-mixing in an ultrasonic mixer at 35 kHz for 1 h.

2.2. Testing equipment

An air-cooled, single-cylinder, compression-ignition (CI), naturally aspirated, four-stroke, direct injection (DI) diesel engine was employed in the experiment. Table 5 displays the primary attributes of the diesel engine employed in this investigation.

All experiments were repeated separately with fuel mixtures at a constant engine speed of 3000 rpm and varying engine loads of 1000 W, 2000 W, 3000 W and 4000 W. The experiments were carried out three times and the experimental data were averaged and plotted. An electronic scale with a mass accuracy of 0.01 g was used to calculate the fuel consumption value. A K-type thermocouple was used to measure the temperature of the exhaust gas. A 20-channel data logger was used for the data from the sensors. Mobydic 5000 COMBI brand exhaust emission device was preferred to measure exhaust emissions. Table 6 lists the technical parameters of the exhaust emission device. Fig. 2 shows the experimental setup schematically.

2.3. Energy analyses

When performing thermodynamic analyzes on internal combustion engines, the first thing to do is to determine the control volume. In the study, the control volume given in Fig. 3 was used for the diesel engine, and balance equations were written according to the conservation of mass and energy. Fuel and air enter the control volume. The heat lost from the exhaust gases and total thermal losses are subtracted from the control volume. In addition, the mechanical power produced by the engine is used as useful work (see Fig. 4).

The application of energy analysis can be expressed as the possibility of evaluating thermal losses and thermal efficiency. Engine power is the useable work produced from the energy of the fuel entering the system. Losses are losses that leave the control volume other than engine power. The amount of energy in the fuel injected into the engine and lost as a result is calculated using energy analysis. Equation [26] is used to calculate engine power.

$$\dot{W} = 2\pi \frac{n}{60} T \tag{1}$$

The engine speed (n) and engine torque (T) are given by abbreviations. The energy balance of the control volume is given in the following equation [27].

$$\dot{E}_f + \dot{E}_a = \dot{W} + \dot{E}_{loss} \tag{2}$$

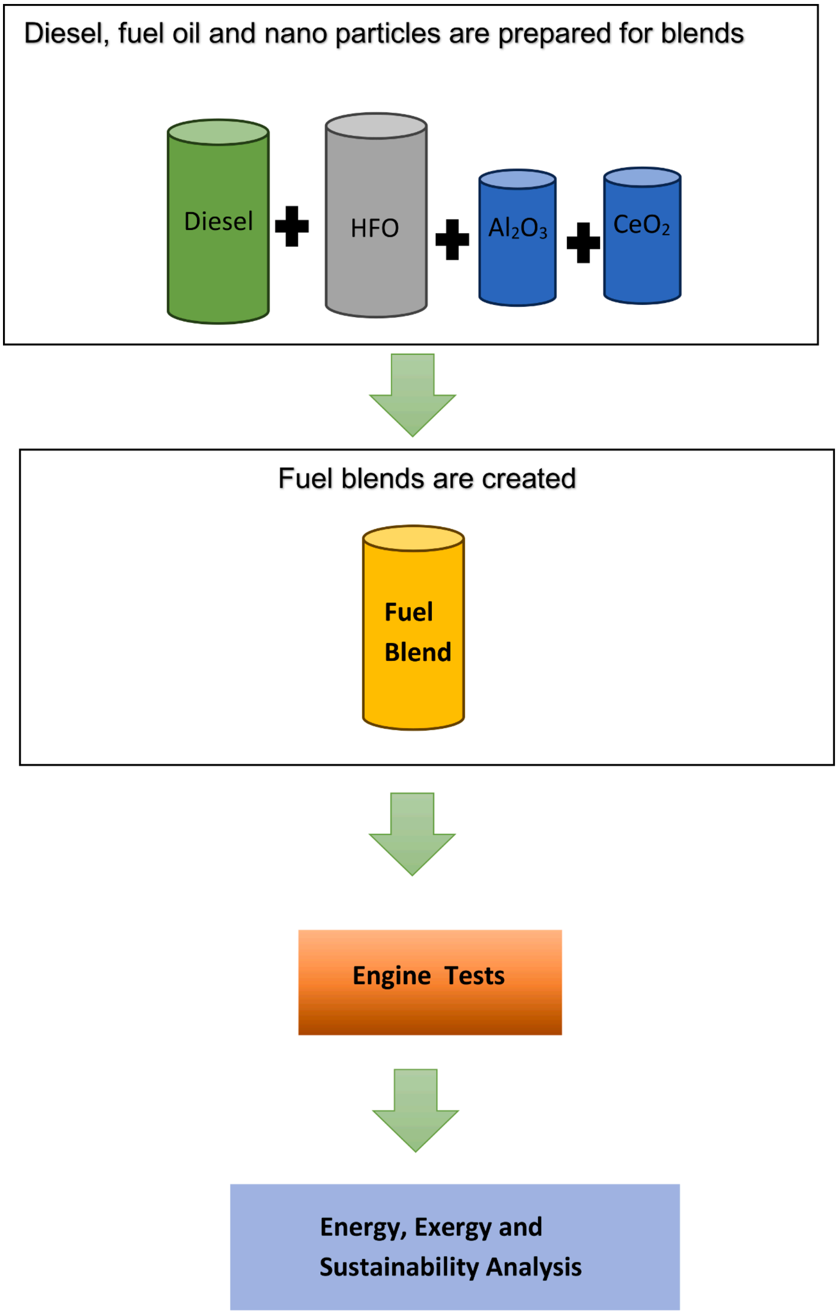


Fig. 1. Flow chart of the study.

Table 1
Chemical and physical properties of HFO with diesel fuel [23].

Properties	Diesel Fuel	HFO
Density (g/cm^3)	859	925
Kinematic Viscosity (40 °C – m^2/s)	3.13	23.6
Flash Point (^{o}C)	52	63
Auto-ignition Temperature (^{o}C)	345	418
Lower Thermal Value (kJ/kg)	42.3	44.72
Cetane Number	52	46

Table 2
Technical characteristics of nanoparticles [24].

Properties	Al_2O_3	CeO_2
Purity (%)	99.9	99.975
Colour	White	Canary
Average Particle Size (micron)	10	8–28
Density (g/cm^3)	3.965	7.2
Crystal Structure	Hexagon	–

Table 3
The measurement method of fuel mixtures and the uncertainty of measurement tools [25].

Properties	Test Method	Diesel Fuel Limits	Device	Sensitivity
Density at 15 °C (kg/cm^3)	TS EN ISO 12185	820–845	KEM DA-640	±0.0001
Kinematic Viscosity at 40 °C (mm2/s)	TS 1451 EN ISO3104	2.00–4.500	TANAKA AKV-202	±0.01
Low Heating Value (kJ/kg)	EN5165	–	IKA C2000	±0.1
Cetane Number	EN ISO5165 TS EN 15195	46 min	BASF	±1
Flash Point (^oC)	TS EN ISO 2719	55 min	RAPID TESTER RT-1	±0.0001

Table 4
Physical and chemical properties of experimental fuel mixtures [25].

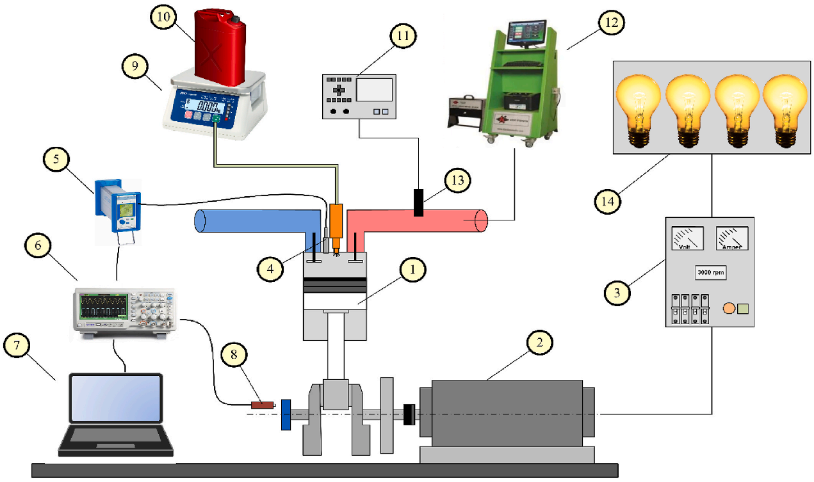
Properties	DF80F20	DF80F20Al25	DF80F20Al100	DF80F20Ce25	DF80F20Ce100
Density at 15 °C (kg/cm^3)	870	873	879	876	880
Kinematic Viscosity at 40 °C (mm^2/s)	7.22	7.23	7.28	7.25	7.3
Low Heating Value (kJ/kg)	42.7	42.7	42.8	42.65	42.61
Cetane Number	51	52	54	53	56
Flash Point (^oC)	55	55	57	56	59

Table 5
The technical specifications of the diesel engine used in the experimental studies.

Diesel engine	
Parameters	Specifications
Model	186 FAG
Number of cycles	4
Number of cylinders	1
Maximum engine power	7 kW (3600 rpm)
Type of fuel	Diesel fuel
Type of ignition	Compression-ignition
Type of fuel injection	Direct injection
Intake system	Naturally aspirated
Engine speed	3000 rpm
Swept volume	418 cm^3
Stroke	70 mm
Bore	86 mm
Cooling system	Air-cooled
Injector nozzle number	4
Pressure of injection	19.6 ± 0.49 Mpa
Fuel delivery advance angle	22 ± 1 (°CA) BTDC
Compression ratio	18:1

Table 6
Technical properties of the exhaust emissions device.

Measurement	Measuring Range	Resolution	Precision
CO (% vol)	0–10	0.01	±1%
CO_2 (% vol)	0–20	0.01	±0.5%
HC (ppm)	0–20000	1	±12
NO_X (ppm)	0–5000	1	±10
O_2 (% vol)	0–21	0.01	±0.5%
Smoke opacity (%)	0–20	0.01	±2



1) Diesel engine, 2) Generator, 3) Generator control panel, 4) Cylinder pressure sensor, 5) Charge amplifier, 6) Oscilloscope, 7) Computer, 8) Crank encoder, 9) Precision scale, 10) Fuel tank, 11) Data logger, 12) Exhaust gas analyzer, 13) K-type thermocouple, 14) Lamp load unit

Fig. 2. Experimental setup.

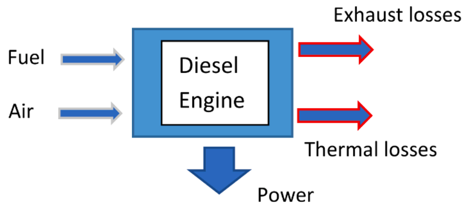


Fig. 3. Control volume.

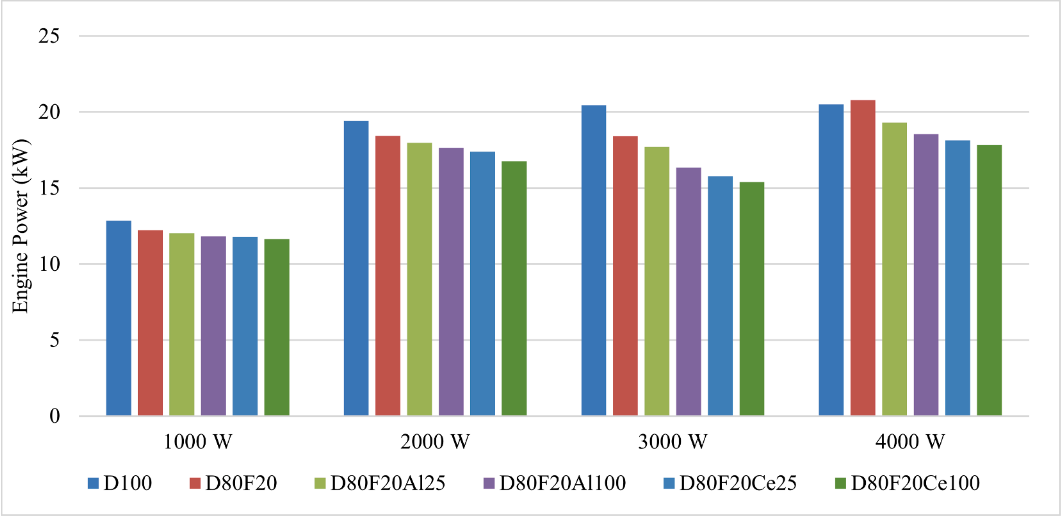


Fig. 4. Calculated exergy destruction at different engine powers.

The engine receives the energy from the air, fuel, and thermal losses ($\dot{E}_a$), fuel energy ($\dot{E}_f$) and thermal losses ($\dot{E}_{loss}$). Exhaust gas energy, the heat lost from the engine's body, the heat transmitted to the cooling water, friction, and any other losses are considered thermal losses. The energy of the air is 0 since it is taken under atmospheric circumstances.

In the test assembly, the mass of fuel injected into the cylinder per unit time ($\dot{m}_f$) is monitored. In a lab setting, the fuel's lower thermal value (H_u) is calculated. The fuel energy is determined using the following equation [28] using these two variables.

$$\dot{E}_f = \dot{m}_f H_u \tag{3}$$

~~Other~~ Total losses in the control volume are determined using equality 4 [29].

$$\dot{E}_{loss} = \dot{E}_f - \dot{W} \tag{4}$$

Thermal efficiency is the ratio of the useful work obtained from the engine to the fuel energy. It is calculated from the following equation [30].

$$\eta_{th} = \frac{\dot{W}}{\dot{E}_f} \tag{5}$$

2.4. Exergy analysis

Fuel exergy is a measure of the ability of an engine cylinder to generate work from the fuel it contains. In this study, exergy analysis is used to identify losses that are not related to the power output of the engine. Articles 1 and 2 of thermodynamics. What is calculated is the exergy lost as a result of applying the law to the control volume. All energy systems aim to reduce the amount of energy lost. Equation (6) [31] contains the exergy balance of the diesel engine used in the research.

$$\dot{E}x_a + \dot{E}x_f = \dot{E}x_w + \dot{E}x_{ex} + \dot{E}x_{heat} + \dot{E}x_{dest} \tag{6}$$

Here the fuel Exergy ($\dot{E}x_f$), the Exergy of the incoming air to the cylinder ($\dot{E}x_a$) and exergetic Power ($\dot{E}x_a$) as shown. Since the air entering the engine is supplied under atmospheric conditions, its exergy is zero Jul. The power obtained from the engine is energetic [32].

$$\dot{E}x_a = 0 \tag{7}$$

$$\dot{E}x_w = \dot{W} \tag{8}$$

Exhaust Exergy ($\dot{E}x_{ex}$), motor Exergy of the Heat lost from the body ($\dot{E}x_{heat}$) and Exergy ($\dot{E}x_{dest}$) control volume Exergy losses. The fuel exergy is calculated from the following equation [33].

$$\dot{E}x_f = \dot{m}_f H_u \varphi \tag{9}$$

Here, theparentfactor) depends on the content of the fuel blends used. After analyzing each fuel blend under laboratory conditions and determining the chemical composition of hydrogen (h), carbon (c), sulphur (α) and oxygen (o), the exergy factor is calculated from equality 10 [34].

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}\left(1 - 2.0628\frac{h}{c}\right) \tag{10}$$

when calculating the exhaust exergy, the actual combustion equation in equation (11) is equalized by using the exhaust emissions measured in the test assembly.

$$a\,(Fuelblend) + b\left(O_2 + 3.76N_2\right) \rightarrow c\,(CO) + d\left(CO_2\right) + e\left(H_2O\right) + f\left(N_2\right) \tag{11}$$

Where a, b, c, d, e and f are the constant numbers required to equalize the equation. The total exhaust gas flow rate ($\dot{m}_{total}$) was calculated from the following equation [3].

$$\dot{m}_{total} = 0.98\dot{m}_f \tag{12}$$

The flow rates of the exhaust gases are determined by considering the ratios in the combustion equation. The exergy of each emission gas is calculated as the sum of its physical (ε_p) and chemical exergies (ε_c) [35].

$$\dot{E}x_{ex,i} = \sum\left(\varepsilon_p + \varepsilon_c\right)_i \tag{13}$$

The following equation, which takes into account the enthalpy (h) and entropy (s) values at the exhaust temperature and ambient temperature, was used to calculate the physical exergy of the exhaust gas. For the dead state characteristics (temperature, enthalpy, and entropy) in equation (14), zero indexes were utilized [36].

$$\varepsilon_p = \tag{14}$$

The chemical exergy of exhaust gases is calculated from the following equation [37].

$$\varepsilon_{ch} = \overline{R}T_0\, ln\frac{1}{y^e} \tag{15}$$

Here, the percentages of the various gases in the atmosphere are (y^e). y^e and the universal gas constant is ($\overline{R}$. The literature's ye values are used [38]. Using the information gathered from the temperature of the engine body (T_s) measurements made with a thermocouple during the trials, equation (16) is used to compute the exergy of heat losses from the engine body.

$$\dot{E}x_{heat} = \sum \left(1 - \frac{T_0}{T_s}\right) \dot{Q}_{loss} \tag{16}$$

The breakdown of exergy is obtained from the following equation [39] in the exergy analysis after determining the exergy of the fuel, energetic power, exhaust, and heat losses from the engine body.

$$\dot{E}x_{dest} = \dot{E}x_f - \left(\dot{E}x_w + \dot{E}x_{ex} + \dot{E}x_{heat}\right) \tag{17}$$

After finding the exergy breakdown, equality 18 [40] is used to compute the entropy production.

$$\dot{s}_{gen} = \frac{\dot{E}x_{dest}}{T_0} \tag{18a}$$

The rate at which fuel exergy is turned into useable work is referred to as exergy efficiency. It is computed using the equation found in Ref. [41].

$$\eta_{ex} = \frac{\dot{E}x_W}{\dot{E}x} \tag{18b}$$

2.5. Sustainability analysis

Exergy efficiency measures how fast fuel exergy is converted into useable energy. The equation given in Ref. [39] is used to calculate this.

$$SI = \frac{1}{1 - \eta_{ex}} \tag{19}$$

3. Result and discussions

In this study, experimental and thermodynamic studies were used to determine the effects of adding nanoparticles to diesel-fuel oil fuel blends in certain amounts. For this purpose, performance and emission experiments were carried out in a single cylinder diesel engine at various powers and constant speeds using fuel blends consisting of diesel, fuel oil and nanoparticles.

Table 7 contains the experimental data obtained from these studies. When the amount of nanoparticles in diesel blends is increased, diesel fuel consumption is significantly reduced. In this study, the performance and emission data recorded from engine tests show similar variations with the data obtained from studies in the literature [13,15,16]. For example, for D80F20CE25 and D80F20CE100 fuel blends, the reduction in fuel consumption is 2.2% and 6.6%, respectively, compared to D80F20 fuel at 4000 W power. CO emissions tend to increase when fuel oil and diesel fuel are mixed. However, CO emissions are significantly reduced when nanoparticles are added to diesel/fuel combinations. Nanoparticles added to fuels cause higher exhaust temperatures. In the study, thermal efficiency, exergy efficiency and sustainability index were calculated using data obtained from engine tests in thermodynamic analysis.

In internal combustion engines, the fuel injected into the cylinder must have a high heating value. The ability of fuels to provide power is determined by their lower heating value, which is expected to be high. In this study, energy and exergy estimates were made using the lower heating value of the fuel as a starting point. This is because the energy produced when the fuel burns under the worst conditions is what the lower heating value represents. The mass flow rate, which is a sign of the lower heating value and fuel consumption, determines the energy of the fuel [42,43]. Fuel consumption and fuel energy are directly related to fuels with the same heating value. However, since various fuels will have varying sub-thermal values, the sub-thermal value, in addition to the change in fuel consumption, is also important in fuel energy estimates. Energy analysis was used in the study to calculate fuel energies, thermal losses and thermal efficiencies of fuel blends. The findings are shown in Table 8.

Diesel/HFO fuel blend has lower thermal energy than D100 fuel. Therefore, the fuel consumption value of D80F20 fuel blend is higher than D100 fuel. Because the lower thermal values of the fuels alone are not enough to change the fuel consumption values. When nanoparticles are added to D80F20 fuel, the lower heating value does not change significantly, but the total fuel energy changes as a result of the reduction in fuel consumption [44]. In contrast, the energy of D80F20AL100 and 80F20CE100 fuels is 22.178 kW and 21.845 kW respectively with 4000 W engine power. Under the same conditions, the fuel energy of D100 fuel is 22,360 kW. When the amount of nanoparticles in diesel fuel blends increases, the diesel fuel blend energy decreases. With D80F20CE25 and D80F20CE100 fuel blends, it is equivalent to 11,503 kW and 11,379 kW respectively at 1000 W engine power. The fuel energy is affected by the nanoparticle type. For example, at 3000 W engine power, the fuel energy for D80F20CE100 and 80F20AL100 fuels is 18.173 kW and 18.709 kW, respectively.

With an increase in engine load, higher thermal losses occur in fuel blends. When nanoparticles are added to fuel blends, thermal losses are reduced. For example, at 4000 W engine load, the D80F20 fuel blend has a thermal loss of 19.677 kW, while the

Table 7
Performance and emissions data.

Fuel consumption (g/kWh)							CO (ppm)					
Power (W)	D100	D80F20	D80F20Al25	D80F20Al100	D80F20Ce25	D80F20Ce100	D100	D80F20	D80F20Al25	D80F20Al100	D80F20Ce25	D80F20Ce100
1000	1002	999	991	982	979	973	0.28	0.45	0.45	0.39	0.3	0.27
2000	779	775	770	763	759	741	0.17	0.36	0.32	0.3	0.26	0.22
3000	589	566	558	532	524	518	0.13	0.38	0.36	0.33	0.3	0.26
4000	478	500	482	473	470	467	0.19	0.58	0.57	0.51	0.45	0.39
O_2 (%vol)							CO_2 (%vol)					
1000	18.33	18.27	18.3	18.32	18.39	18.41	2.17	2.12	2.15	2.16	2.19	2.21
2000	18.45	18.33	18.36	18.44	18.47	18.51	1.93	1.85	1.87	1.9	1.93	1.98
3000	18.03	18.01	18.06	18.09	18.13	18.16	1.75	1.63	1.64	1.71	1.82	1.85
4000	19.01	18.99	19.02	19.11	19.12	19.17	1.89	1.73	1.75	1.81	1.86	1.88
Exhaust temperature (K)							NOx (ppm)					
1000	349	350	352	361	359	367	113	118	125	132	129	133
2000	438	441	451	459	451	458	119	123	129	136	134	145
3000	496	502	508	512	509	513	141	152	159	165	160	169
4000	587	589	591	603	593	602	159	162	165	173	169	181

Table 8
Results of energy analysis calculations.

Power (W)	Fuel Blends	Fuel Energy (kW)	Thermal Losses (kW)	Thermal Efficiency (%)
1000	D100	11.718	10.718	8.534
	D80F20	11.826	10.826	8.456
	D80F20Al25	11.672	10.672	8.568
	D80F20Al100	11.511	10.511	8.687
	D80F20Ce25	11.503	10.503	8.693
	D80F20Ce100	11.379	10.379	8.788
2000	D100	18.220	16.220	10.977
	D80F20	18.349	16.349	10.900
	D80F20Al25	18.138	16.138	11.027
	D80F20Al100	17.888	15.888	11.181
	D80F20Ce25	17.837	15.837	11.213
	D80F20Ce100	17.331	15.331	11.540
3000	D100	20.664	17.664	14.518
	D80F20	20.101	17.101	14.924
	D80F20Al25	19.716	16.716	15.216
	D80F20Al100	18.709	15.709	16.035
	D80F20Ce25	18.471	15.471	16.242
	D80F20Ce100	18.173	15.173	16.508
4000	D100	22.360	18.360	17.889
	D80F20	23.677	19.677	16.894
	D80F20Al25	22.708	18.708	17.615
	D80F20Al100	22.178	18.178	18.036
	D80F20Ce25	22.090	18.090	18.108
	D80F20Ce100	21.845	17.845	18.311

D80F20CE100 and D80F20AL100 fuel blends have thermal losses of 17.845 kW and 18.178 kW, respectively. The thermal losses in the fuel blends were reduced by adding more nanoparticles. At an engine load of 2000 W, the thermal losses in D80F20CE100 fuel are 3.2% lower than in D80F20CE25 fuel. Under the same conditions, the D80F20AL100 fuel blend was reduced by 1.5% compared to the D80F20AL25 fuel blend.

According to the study, thermal efficiency increases as engine power increases. For example, the thermal efficiency of the D80F20 fuel blend is 8.456% at 1000 W engine load, while it is 16.894% at 4000 W engine power. Other fuel blends show similar changes. The hazard increases when nanoparticles are added to fuel blends. The thermal efficiencies of D80F20, D80F20AL100 and D80F20CE100 fuels are 14.924%, 16.035% and 16.508% respectively at 3000 W engine power. The thermal efficiency of fuel blends increases as the amount of nanoparticles increases. Also, the thermal efficiency of fuel blends containing CeO_2 nanoparticles is higher compared to fuels with Al_2O_3 nanoparticles. The addition of nanoparticles to D80F20 fuel reduces the viscosity. Reduced viscosity increases chemical reactivity, thus providing better combustion and increasing thermal efficiency [41,42].

The purpose of engine thermodynamic evaluations is to calculate the losses caused by irreversibilities. If these irreversibilities are reduced, efficiency will increase. In the study, energy analysis was used to evaluate the thermal efficiency of the fuel blends and then exergy analysis was used to estimate the second law efficiencies.

Table 9 shows the information obtained from the exergy study. As the engine load increases, the exergy of the fuel blends also increases. The exergy of the fuel depends mainly on the chemical exergy factor, the lower heating value and the fuel consumption. The subheating value and the chemical exergy factor are constant with engine power. An increase in fuel consumption increases the fuel exergy. An increase in fuel consumption increases irreversibilities. Therefore, an increase in fuel exergy may not lead to positive improvements. The highest fuel exergy is 30,520 kW for the D80F20 fuel with an engine load of 4000 W. This is a result of the fact that D80F20 fuel has a lower heating value and higher fuel consumption than D100 fuel. When nanoparticles are added, the energy of the fuel is reduced because fuel utilization is also reduced. When the number of nanoparticles in diesel/HFO fuel blends increases, the energy of the diesel/HFO fuel blend decreases. For example, at the output of a 4000 W engine, the exergy of D80F20CE25 and D80F20CE100 fuels is 28,479 kW and 28,163 kW respectively.

Emission data were used in exhaust exergy calculations. CO_2 emissions are lower for D80F20 fuel than for D100 fuel at all engine powers. However, CO emissions of D80F20 fuel are significantly higher than D100 fuel at all engine powers. The addition of nanoparticles to D80F20 fuel shows an improvement in emissions. Therefore, the lowest exhaust exergy is calculated for D100 fuel at all engine loads. For example, the exhaust energy for D100, D80F20 and D80F20AL100 fuels with 3000 W engine power is 1731 kW, 1734 kW and 1730 kW respectively. While the exhaust energy of D80F20 fuel increased, it showed a decreasing trend with the addition of nanoparticles. The exhaust exergy of D80F20CE25 and D80F20CE100 fuels are 2462 kW and 2454 kW respectively for an engine with an output of 4000 W. According to Anderson et al. [45], the addition of nanoparticles to biodiesel fuel improves exhaust emissions. Especially improvements in CO emissions were observed. According to the study, the oxygen content of D80F20 fuel was increased by adding nanoparticles. As a result, both exhaust temperature and combustion temperature in the cylinder increase [46,47]. In this sense, the results of the study are like the study in the literature.

Better combustion of the fuel was possible due to the nanoparticle additions that increased the temperature inside the cylinder. As a result of the increase in in-cylinder temperature, the casing temperature of the heat engine increased. Experimental research has

Table 9
Results of exergy analysis calculations.

Power (W)	Fuel Blends	Fuel Exergy (kW)	Exhaust exergy (kW)	Exergy of thermal losses (kW)	Exergy Efficiency (%)
1000	D100	15.804	0.973	0.980	6.33
	D80F20	15.247	0.990	1.031	6.56
	D80F20Al25	15.047	0.992	1.042	6.65
	D80F20Al100	14.840	0.985	1.048	6.74
	D80F20Ce25	14.830	0.977	1.054	6.74
	D80F20Ce100	14.670	0.972	1.052	6.82
2000	D100	24.573	1.250	1.897	8.14
	D80F20	23.656	1.261	1.973	8.45
	D80F20Al25	23.384	1.256	2.151	8.55
	D80F20Al100	23.062	1.255	2.167	8.67
	D80F20Ce25	22.995	1.251	2.352	8.70
	D80F20Ce100	22.344	1.249	2.348	8.95
3000	D100	27.869	1.731	2.690	10.76
	D80F20	25.915	1.734	2.771	11.58
	D80F20Al25	25.418	1.731	2.993	11.80
	D80F20Al100	24.120	1.730	3.037	12.44
	D80F20Ce25	23.813	1.734	3.303	12.60
	D80F20Ce100	23.429	1.730	3.298	12.80
4000	D100	30.156	2.455	3.204	13.26
	D80F20	30.524	2.477	3.268	13.10
	D80F20Al25	29.275	2.474	3.497	13.66
	D80F20Al100	28.593	2.467	3.584	13.99
	D80F20Ce25	28.479	2.462	3.896	14.05
	D80F20Ce100	28.163	2.454	3.889	14.20

measured the casing temperature of the engine. These facts allowed the calculation of the exergy of heat transfer through the engine casing. As the engine power increases, thermal losses and heat conduction also increase. At all engine powers and using D100 fuel, the lowest engine casing temperature was recorded. Therefore, the energy produced by D100 fuel calculated the lowest thermal losses among all fuel blends. The addition of nanoparticles increases the exergy brought about by thermal losses. The exergy of thermal losses in D80F20, D80F20AL100 and D80F20CE100 fuels are 3268 kW, 3584 kW and 3889 kW, respectively, when the engine load is 4000 W. According to the experiments of Channapattana et al. [48], nickel oxide nano additions minimized the energy losses. Therefore, it is possible to mention the effect of nanoparticle addition on energy reduction in this study.

Exergy losses from the engine body and the exhaust were quantified in the study, and all other exergy losses were treated as disappearing exergy. The variation in wasted energy based on motor power is seen in Fig. ~~3~~ 4. The irreversibility in the cylinder rises as engine power increases. The fuel's exergy vanishes because of this. In the case of D80F20 fuel, the energy wasted at 1000 W and 4000 W engine outputs, respectively, is 12.22 kW and 20.78 kW. Other fuels mixtures show a similar pattern of behaviour. The quantity of energy that dissipates lowers when nanoparticles are introduced to D80F20 fuel because a drop in fuel consumption results in a decrease in irreversibilities. The energy wasted in the D80F20, D80F20AL100, and D80F20CE100 fuels is 18.41 kW, 16.35 kW, and 15.4 kW, respectively, for an engine with a 3000 W output. The wasted energy is decreased when the fuel blend contains more nanoparticles. The energy wasted in the D80F20CE25 and D80F20CE100 fuels is 19.31 kW and 18.54 kW, respectively, when the engine power is 4000 W. The disappearing exergy of D80F20 fuel depends on the type of nanoparticle added. The use of CeO2 in D80F20 fuel caused lower exergy degradation compared to the use of Al_2O_3. Entropy production is obtained by dividing the destroyed exergy by the temperature. For this reason, the exergy results that disappear in fuel blends are used as entropy production data when divided by a temperature of 298 K. Ağbulut [42] stated in his study that the use of nanoparticles in fuel blending reduces exergy degradation. In the study, the exergy degradation of the C10 + 28 nm TiO_2 fuel blend is lower compared to DF and C10 fuels. Karagoz et al. [44] in their study, they showed that exergy degradation is low in fuel blends using nanoparticles. The lowest and highest exergy degradation in the study was realized in D90B10AL100 and D90B10 fuels, respectively. In the evaluation of fuel blends, fuels with low exergy degradation may be a better option [41]. Aghbashlo et al. [48] in their study, the exergy destruction rates of pure diesel and B5W3m (95% diesel +5% biodiesel mixture (B5) with 90 ppm CeO_2 nanoparticle added) fuel blend were 28.36% and 28.26%, respectively.

Fig. 5 of the study shows the energy and exergy efficiency depending on the motor load. The oxygen supplied by the nanoparticles improves combustion and reduces the proportion of unburned fuel. Fuel blends that increase engine power also reduce fuel consumption, resulting in a gain in energy and thermal efficiency. For example, engines with 1000 W and 4000 W output using D80F20 fuel have a thermal efficiency of 8.6% and 16.89% respectively. The energy efficiency is 6.56% and 13.11% respectively under the same conditions. The efficiency of the fuel blends increased with the addition of nanoparticles. The thermal efficiency of D80F20AL100 and D80F20CE100 fuels is 6.32% and 7.73% higher than that of D80F20 fuel at 4000 W engine power, respectively. This is also true for energy efficiency. Efficiency is increased by adding more nanoparticles to the fuel blend. Nanoparticles are added to fuel blends to improve combustion efficiency, improve combustion in the cylinder and accelerate heat transfer [29]. In addition, the energy and exergy efficiency depends on the type of nanoparticle. When CeO_2 is used as nanoparticle, the efficiency is higher than when Al_2O_3 is used at all engine powers. This is also proved by similar studies in the literature. For example, Özcan [47]

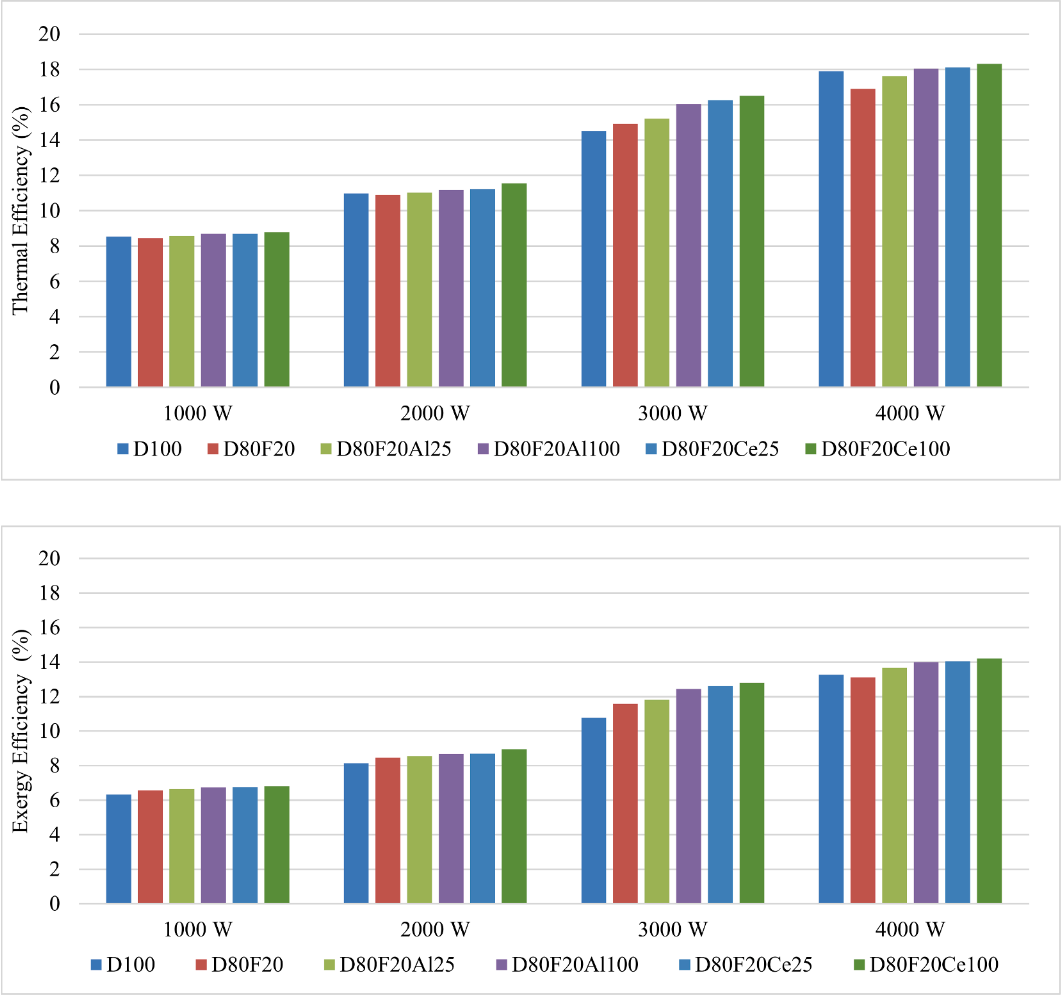


Fig. 5. Energy and exergy efficiency.

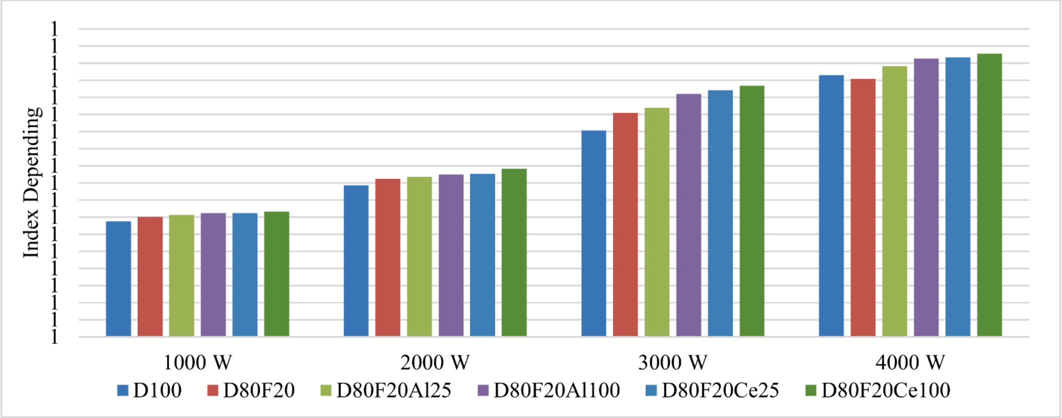


Fig. 6. Sustainability index depending on engine power.

found that when Al_2O_3 nanoparticles were added to diesel/biodiesel fuel blend at 50 ppm and 100 ppm, energy efficiency increased by 7.8% on average (see Fig. 6).

The ratio of fuel energy to energy losses brought on by irreversibilities is utilized in sustainability studies. The index produced by this investigation can be used to compare fuel mixes. During cylinder combustion, fuel's sustainability rises as its irreversibility diminishes. ~~The study's fuels' sustainability index, shown in~~ Fig. 1~~, is provided as 5.~~ The sustainability index of the fuels used in the study is given in Fig. 5. All fuel blends have higher sustainability indices as energy efficiency rises. The sustainability rating has gone up since D80F20 fuel now contains nanoparticles. For instance, the D80F20 and D50F20CE100 fuels with an engine power of 4000 W have sustainability indices of 1.151 and 1.166, respectively. The sustainability score does not significantly rise when the amount of nanoparticles in D80F20 fuel is increased. The sustainability index of the D80F20CE100 fuel is 0.3% greater than that of the D80F20CE25 fuel for engines with a 4000 W output. The type of nanoparticles has a minimal impact on the sustainability rating. In his research, Ağbulut [42] has demonstrated that the sustainability index rises when the motor load is fired. He claimed in his investigation that the addition of TiO_2 nan particles to C10 fuels raised the sustainability score. In their investigation, Karagoz et al. [44] computed the fuel mix sustainability indices in the range of 1.135–1.391 in December. When nanoparticles are added to fuel mixtures, the index rises. The sustainability indices of pure diesel and the B5W3M fuel blend were 1.69 and 1.52, respectively, according to Aghbashlo et al.'s study [48]. The B5W3M fuel blend is the alternative fuel that comes closest to pure diesel.

4. Conclusions

This study used fuel blends made from fuel oil and nanoparticles in a diesel engine to do engine testing in a lab setting at various engine powers. Utilizing the information gathered from these tests, evaluations of energy, efficiency, and sustainability were performed. At all engine powers, D80F20 fuel has a lower energy and exergy efficiency than D100 gasoline. The energy and exergy efficiencies of the D80F20 fuel, however, are better than those of the D100 fuel thanks to the inclusion of nanoparticles. This study focuses on the effect of the addition of AL_2O_3 at all CeO_2 as nanoparticles to diesel/HFO fuel blends on combustion, emissions, energy and exergy efficiency by thermodynamic analysis. The thermal efficiency and exergy efficiency of diesel fuel HFO blends decrease compared to pure diesel fuel. However, the addition of nanoparticles to diesel/HFO blends has a positive effect on energy and exergy efficiency. When nanoparticles were added to D80F20 fuel, the exhaust exergy increased but the exergy of thermal losses and the values of lost exergy decreased. When the engine load is 2000 W, the energy dissipation for D80F20, D80F20AL100 and D80F20CE100 fuels are 18.423 kW, 17.640 kW and 16.747 kW respectively. As the number of nanoparticles in the fuel blends increases, the thermal and energy efficiency of the fuel blends increases. D80F20CE100 fuel has 2.8% more energy efficiency than D80F20CE25 fuel when the engine power is 2000 W. Among the nanoparticles used in the tests, CeO_2 has lower energy losses than Al_2O_3 at all engine loads. Therefore, it is more effective. In the calculations, with the addition of nanoparticles to the D80F20 fuel blend, the sustainability index of the fuel blends was higher than 1. This shows that the addition of nanoparticles to alternative fuels has positive results.

CRediT authorship contribution statement

Battal Doğan: Data curation, Methodology, Software, Visualization, Writing – review & editing. **Salih Özer:** Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Project administration, Resources. **Erdinç Vural:** Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Ahmet Fatih Haciyusufoğlu:** Formal analysis, Investigation, Methodology, Writing – original draft.

Declaration of competing interest

The author 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

No data was used for the research described in the article.

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