THERMODYNAMIC ANALYZES IN A COMPRESSION IGNITION ENGINE USING FUEL OIL DIESEL FUEL BLENDS

by

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We use fuel oil as an alternative fuel in compression ignition engines without modification. In this study, we performed tests at different engine speeds using diesel fuel oil fuel blends in a compression ignition engine. Energy and exergy analysis was carried out using the performance and emission values got from these tests. Through energy analysis, the energy distribution of the engine was determined and the thermal efficiency was calculated. The highest thermal efficiency is 34.76% on F40 fuel at 2250 rpm. In the exergy analysis, fuel exergy, exhaust exergy, entropy production, and exergy efficiency were calculated. The highest exergy destruction is 17.36 kW at 3250 rpm on D100 fuel. The exergy efficiency increases with engine speed. The highest exergy efficiency is 28.2% on F40 fuel at 2250 rpm.

Key words: *fuel oil, diesel, energy, exergy*

Introduction

Currently, petroleum-based fuels are usually used as energy sources in the engines of vehicles used in the transport sector. Because of the combustion of these fuels in the cylinder, environmental pollution occurs and threatens human health. Alternative fuel studies have gained momentum over the last 20 years because of the depletion of oil resources [1]. However, because of all the studies conducted to this day, it has not been possible to completely abandon the use of petroleum-based fuels. When the studies in the literature are examined, we saw that all fuels and fuel mixtures used in diesel engines cause environmental problems [2]. Therefore, minimizing emissions in alternative fuel studies in Diesel engines should be the goal. In order to reduce the emissions released into the atmosphere from diesel engines and causing environmental pollution, it is necessary to improve the quality of combustion, reduce low fuel consumption, thermal losses and reduce the due time of the engine [3, 4]. But it may not always be possible to realize these recommendations. The American Society for Testing and Materials (ASTM) has classified diesel fuels [5]. Got from the distillation of petroleum No.1-D diesel is currently used in engines where frequent changes in speed and loads are required. Got by distillation of very dark No.4-D diesel (fuel oil) is preferred for medium and low speed engines. Fuel oil, which is the lowest grade in fuel oils, is black and is a liquid fuel. From an economic point of view, fuel oil has a lower cost compared to diesel fuel [6]. The viscosity of the fuel used in diesel engines is important [7]. Low viscosity fuels enter the cylinders as smaller parts, which

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increases the combustion efficiency. High viscosity creates a difficulty in pumping and spraying in injectors and increases the amount of energy spent. The viscosity of fuel oil is quite high compared to diesel fuel. For this reason, we should take precautions to address viscosity-related problems in using fuel oil in Diesel engines. In the literature, fuel oil is referred to as heavy fuel [8]. One of the most important characteristics of the fuels to be used in Diesel engines is the cetane number [9]. A high number of cetanes, which play an important role in fuel performance, provide a shorter ignition delay. The cetane number of fuel oil fuels is close to diesel fuel. The characteristic for the safe use of fuels in vehicles is the flash point [10]. We can safely use it in fuel oil Diesel engines with a high flash point. The amount of sulfur in the fuel is the main cause of engine wear. We consider a high amount of sulfur in its structure a disadvantage in using fuel oil as a fuel. Carbon and ash accumulated at the end of combustion pose a problem in Diesel engines [11]. For this reason, there are problems with the use of fuel oil as a fuel with a high ash content in Diesel engines. In addition, fuel oil produces a large amount of harmful exhaust emissions during combustion [12]. The most important advantage of fuel oil is its low price. It is also a good alternative fuel for power generation in engines because of its high energy density. For the use of fuel oil as a fuel in Diesel engines, various additives can be added. Stamoudis *et al.* [8] in their studies, they used organometallic compounds based on fat-soluble Ca (A1) and fat-soluble Fe (A2) as additives to HFO. With the addition of additives (A1 and A2), fuel consumption decreased by 2.22% and 1.21%, respectively. In A1 and B1 fuels, there was a decrease in exhaust gas temperature by 2.67% and 2.42%, respectively. There was a significant decrease in NO_x emissions from additives by 23.02-32.61%. They inject H_2 into the HFO fuel. In the case of H_2 injection in a two-stroke Diesel engine used as an HFO fuel, efficiency increases by more than 53% [13]. In addition, if they switch the dual combustion mode in addition about 0.78 tons will reduce the H_2 injection in this engine [MWh] at full power. The HFO fuel has a high carbon and low oxygen content [14]. Someone can emulsify it with water in order to reduce the harmful emissions resulting from HFO combustion. Water emulsion in HFO increases combustion and reduces emissions of SO_x, NO_x and particulate matter [15]. Using low cost HFO instead of diesel fuel in compression ignition engines reduces costs in power generation. Feng *et al.* [16], they showed that the performance and thermal efficiency did not change because of using diesel fuel in the same engine with a diesel-heavy diesel mixture with a water content of 10% and diesel fuel. The chemical structure of fuel oil is very complex [17]. Besides performance and absorption tests, thermodynamic analyses are used in alternative fuel studies in Diesel engines. Thermodynamic analysis is used to calculate the exergy of the fuel, thermal efficiency, exergy efficiency, entropy generation and vanishing exergy. Hosseinzadeh-Bandbafha *et al.* [18] conducted tests using diesel-biodiesel-bioethanol mixtures in a heavy-duty tractor Diesel engine. Using the data obtained from the tests, it was determined that biodiesel and bioethanol are suitable alternative fuels for generating power in tractors working in agricultural fields with exergy, economic and environmental analysis. Fuel oil, which is economically helpful and environmentally disadvantageous compared to diesel fuel, can be used in heavy-duty Diesel engines in areas far from urban centers, construction sites and agricultural areas.

In the literature, studies have been conducted in which many fuel mixtures such as diesel, biodiesel, alcohols, nanoparticles, LPG, and CNG have been used in Diesel engines. In addition performance and emission measurement, thermodynamic analysis studies are at a lower level in these studies. Studies on the use of fuel oil in a Diesel engine are very limited. Due to the environmental disadvantages of fuel oil, alternative fuel studies in Diesel engines have been limited. In this study, performance and emission tests of diesel-fuel oil blends were carried out. The changes of fuel oil emissions according to diesel fuel have been determined.

Thermal efficiency and exergy efficiency in the case of using fuel oil as an alternative fuel have been calculated by energy and exergy analysis.

Materials and methods

The fuel oil used for engine experiments was supplied from a local manufacturer. The fuel mixed with diesel fuel is commercially referred to as fuel oil 5. The experimental fuels were mixed volumetrically. In order to ensure the fluidity of the fuel oil, the fuel mixtures were heated and mixed. Fuel mixtures were prepared volumetrically during engine experiments. In the graphs, D denotes 100% diesel fuel, F denotes 100% No. 5 fuel oil fuel, F20 denotes 80% diesel + 20% fuel oil fuel, and F40 denotes 60% diesel + 40% fuel oil fuel mixtures. The physical properties of the experimental fuels are given in tab. 1.

Table 1. Technical properties of fuels used in experimental study

Parameters	D	F	F20	F40
Density [kgm^{-3}]	859	903	871	884
Kinematic viscosity 40 °C [mm^{2}s^{-1}]	3.13	28.78	21.12	15.45
Lower thermal value [kJkg^{-1}]	42.1	44.69	42.9	43.1

The engine experiments were carried out in the engine test apparatus, the schematic picture of which is given in fig. 1. The characteristics of the experimental engine are given in tab. 2. Engine experiments were carried out in the position of the full throttle lever of the engine. In the experimental set-up installed for this purpose, the engine was tested with each mixture ratio at 1250 rpm, 1750 rpm, 2250 rpm, 2750 rpm, and 3250 rpm engine speeds.

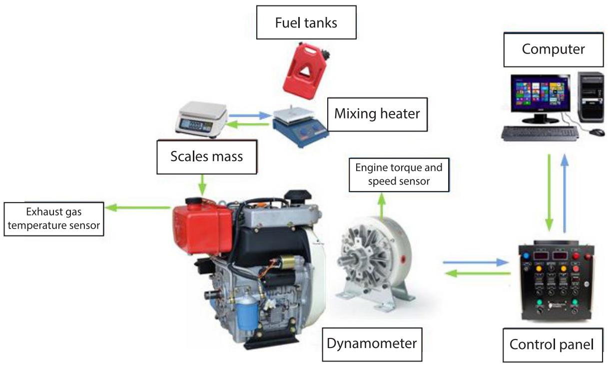

Figure 1. Schematic picture of the experimental set-up

Table 2. The characteristics of the experimental engine

Engine	Four strokes, direct injection, air-cooled and naturally aspirated
Model	186 FAG
Number of cylinder	1
Intake system	Naturally aspirated
Bore × 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

During the engine experiments, the fuel consumption value, the exhaust gas temperature value were recorded. All tests were expected to be heated before and the heating operations were carried out with diesel fuel. All fuel mixtures were continuously supplied to the engine to reach a temperature of 50 °C in a heater before being sent to the Diesel engine.

Energy analyses

First law of thermodynamics for the input and output terms of a compression ignition engine, which is considered to be the control volume in the analysis of the study. If the law is applied [19]:

$$\sum \dot{E}_{\text{air}} + \sum \dot{E}_{\text{fuel}} = \sum \dot{E}_{\text{work}} + \sum \dot{E}_{\text{loss}} \tag{1}$$

The energy of air and fuel refers to the energy entering the engine. Since air enters the engine under atmospheric conditions, its energy is considered zero. As a result of combustion of fuels in the cylinder, heat energy is converted into mechanical energy. This is shown as mechanical energy, $\dot{E}_{\text{w}}$, and all losses in the engine, $\dot{E}_{\text{loss}}$. Usually, when calculating the energy released as a result of combustion processes, the lower thermal value of the fuel is an important parameter. This parameter is used in the comparison of fuels in thermodynamic analysis. The energy of the fuel, $\dot{E}_{\text{f}}$, can be calculated from eq. (2) using the lower thermal value, H_u, and flow rate, $\dot{m}_{\text{f}}$. Losses in the engine, $\dot{E}_{\text{loss}}$, were determined using eq. (3) in order to find the energy distribution [20, 21]:

$$\dot{E}_{\text{f}} = \dot{m}_{\text{f}} H_u \tag{2}$$

$$\dot{E}_{\text{loss}} = \dot{E}_{\text{f}} - \dot{W} \tag{3}$$

The parameter that shows how much of the fuel energy is converted into engine power is the thermal efficiency, η, [22, 23]:

$$\eta = \frac{\dot{E}_{\text{w}}}{\dot{E}_{\text{f}}} \tag{4}$$

Energy analyses

In this study, exergy analysis was performed to compare diesel fuel oil blends. In the exergy analysis, the assumption was made that the engine is running in a black state and the exhaust gases are the ideal gas. The ambient pressure and temperature were taken as 1 bar and 298 K, respectively. The exergy balance of the control volume is shown in eq. (5) [24]. Here the fuel exergy, $\dot{E}x_{\text{f}}$, exhaust gas exergy, $\dot{E}x_{\text{exh}}$, thermal exergy losses, $\dot{E}x_{\text{heat}}$, and exergy destruction, $\dot{E}x_{\text{dest}}$, is. Exergetic work is taken equal to engine power [25]:

$$\dot{E}x_{\text{f}} - \left(\dot{E}x_{\text{w}} + \dot{E}x_{\text{exh}} + \dot{E}x_{\text{heat}} \right) = \dot{E}x_{\text{dest}} \tag{5}$$

The chemical exergy of fuel mixtures is calculated from eq. (6) using the fuel properties given in tab. 1 [26]. Where ε_{f} is the specific exergy and φ is the exergy factor. The exergy factor can be determined by eq. (7) using the ratios of H, O, C, and S obtained from the fuel analysis [27]:

$$\dot{E}x_{\text{f}} = \dot{m}_{\text{f}} \varepsilon_{\text{f}} = \dot{m}_{\text{f}} H_u \varphi \tag{6}$$

$$\varphi = 1.0401 + 0.1728 \frac{H}{C} + 0.0432 \frac{O}{C} + 0.2169 \frac{S}{C} \left(1 - 2.0628 \frac{H}{C} \right) \tag{7}$$

When calculating the exergy of exhaust gases, the total mass of combustion products is determined by the eqution above:

$$m_t = \sum_i m_i \tag{8}$$

The physical exergy of combustion products, $\dot{E}_{ph}$, is calculated from eq. (9), and the chemical exergy, $\dot{E}_{ch}$, is calculated from eq. (10) [28-31]. The dead state is indicated by the index 0. For the y^e-value used in chemical exergy calculations, the mole fraction of the reference surrounding components was used [32]. Exhaust exergy is the sum of physical and chemical exergies:

$$\dot{E}x_{phy} = \left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \tag{9}$$

$$\dot{E}x_{ch} = \bar{R} T_0 ln \frac{1}{y^e} \tag{10}$$

where $\bar{R}$ is the universal gas constant, s – the entropy, and T_0 – the ambient temperature.

The exergy of thermal losses from the control volume to the environment is calculated from the eq. (11) depending on the nominal surface temperature, T_w, and heat loss, $\dot{Q}_{loss}$, [33]:

$$\dot{E}_{heat} = \Sigma\left(1 - \frac{T_0}{T_w}\right)\dot{Q}_{loss} \tag{11}$$

The exergy efficiency can be found by using exergetic work with the exergy of fuels [34]:

$$\psi = \frac{\dot{E}x_w}{\dot{E}x_f} \tag{12}$$

The exergy destruction and entropy generation were calculated from [35]:

$$\dot{E}x_{dest} = \dot{E}x_f - \left(\dot{E}x_w + \dot{E}x_{exh} + \dot{E}x_{heat}\right) \tag{13}$$

$$\dot{S}_{gen} = \frac{\dot{E}x_{dest}}{T_0} \tag{14}$$

Results and discussion

The effect of adding fuel oil to diesel fuel on BSFC is given in fig. 2. The fuel consumption value varies according to the speed of the engine. In addition, with the addition of fuel oil to diesel fuel, there is a decrease in the amount of BSFC in the F20 and F40 fuel mixtures. This is due to the increased thermal value of fuel oil. It has been observed that the increased thermal value is effective in reducing the amount of BSFC.

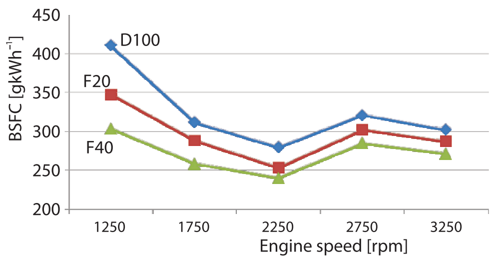

Figure 2. Fuel consumption of fuel blends at different engine speeds

Fuel consumption is high at low revs. The lowest fuel consumption at 2250 rpm was achieved in all fuel mixtures. After this cycle, the fuel consumption increases. The lowest fuel consumption is 271 g/kWh on F40 fuel at 2250 rpm. A number of disadvantages, such as increased friction losses, increased heat losses, and worsening combustion conditions, lead to increased specific fuel consumption. Engine power is obtained from a certain ratio of the energy of the fuels received in the cylinder. Energy other than engine power is considered to be lost. These losses are mainly the heat released into the environment from the exhaust, the cooling system and the engine body. In addition, there is friction, mechanical and other losses in the engine [22]. In the study, fuel energy, power and losses are determined and given in tab. 3. As the engine speed increases, the energy of the fuels increases depending on the fuel consumption [20]. When using D100 fuel, the engine speed increased from 1250 rpm to 3250 rpm, and its energy increased by about 2.54 times. The lower thermal value of the fuel oil is higher than that of diesel fuel. After passing the fueloil 60% ratio in fuel blends, its energy is higher than D100 fuel. When the thermal losses in the engine were examined, lower thermal losses were formed in the F20 and F40 fuels than in the D100 fuel. As the fuel oil ratio increases in fuel blends, thermal losses are observed to increase. The lowest thermal loss value was calculated for 7.739 kW of F40 fuel at an engine speed of 2250 rpm. At the same time, it was calculated as 8.929 kW in D100 fuel. The results of the study are similar to [23, 28] in the literature.

Table 3. Energy analysis results of test fuels

Fuel	Fuel energy [kW]				
	1250 rpm	1750 rpm	2250 rpm	2750 rpm	3250 rpm
D100	8303	10291	12864	18477	21050
F20	7221	9826	11957	18349	20717
F40	6950	9466	11862	17973	20250
	Heat Losses [kW]				
D100	6575	7469	8929	13553	15094
F20	5467	6949	7975	13223	14625
F40	5038	6405	7739	12703	14022

In the study, the part of the heat energy generated as a result of the combustion of fuels that turns into mechanical energy was determined in the test device. The availability of fuels was calculated by exergy analysis. In addition, the exhaust exergy resulting from the combustion of each fuel, the total exergy of heat losses and the exergy destruction were determined. The results of the exergy current of the fuels are given in tab. 4. Fuel exergy increases in direct proportion engine speed. In F40 fuel, the exergy is 24.99 kW at 3250 rpm and 14.639 kW at 2250 rpm. The exergy increase rate is higher at high speeds than at low speeds. The lowest fuel exergy is manifested in F40 fuel at all engine speeds. In the case when the engine speed is 2250 rpm, the exergy of the D100, F40 and F90 fuels is 17.349 kW, 14.639 kW and 18.31 kW, respectively. The results obtained are similar to the results of previous studies [23, 25] The exergy of pure diesel fuel at full load is 8.43 kW.

Table 4. Exergy current of fuel blends

		Engine speed [rpm]				
Exergy of fuel [kW]	Fuel mixture	1250	1750	2250	2750	3250
	D100	11.198	13.879	17.349	24.920	28.390
	F20	9.326	12.689	15.441	23.696	26.754
	F40	8.577	11.682	14.639	22.181	24.990

As shown in tab. 5 in the study, the exhaust exergy increases depending on the engine speed. The exhaust exergy of F40 fuel is 1.813 kW at 2250 rpm engine speed and 2.149 kW at 3250 rpm. The exergy of heat losses was calculated using the cooling system and the losses from the engine body to the environment. Among the fuel blends, the exergy caused by heat loss in F40 fuel is the lowest at all engine loads. Since the increase in the number of engine revolutions increases the increase in heat losses, the exergy increases. If the engine load is 1250 rpm and 3250 rpm in F40 fuel, the exergy caused by heat loss of 0.709 kW and 2.521 kW, respectively, has been calculated. Sarıkoc *et al*. [28] calculated the exergy at 1400 rpm in biodiesel, the exhaust exergy is 12.29%, the cooling water exergy is 7.33%, the brake power exergy is 29.77% and the exergy destruction is 50.60%. Das *et al.* [26] reported in their study that exhaust exergy decreases with the addition of pyrolytic waste plastic oil to pure diesel fuel. The addition of waste oil with a high thermal value allowed combustion become more efficient, reducing exhaust exergy. Sanli *et al*. [33] have stated that the exergy decimation rate of fuels at 1800 rpm is between 45-50 kW, and it rises above this value at high engine speeds. The exergy destruction was calculated using fuel exergy, engine power and exergy of all losses. The ratio of exergy destruction is the largest part in the conversion of fuel exergy. In the evaluation of alternative fuels, fuels with low exergy destruction are the reason for preference. In the study, the exogenous destruction of fueloil diesel fuel mixtures increases due to an increase in the number of engine revolutions. If the engine speed is 1250 rpm, 2250 rpm, and 3250 rpm on F40 fuel, the exergy destruction is 4.723 kW, 7.59 kW, and 14.092 kW. The number of engine revolutions causes a noticeable increase in exergy destruction. An increase in the proportion of fuel oil in fuel blends affects the destruction of exergy. Karagoz *et al*. [23] have determined that the exergy destruction rate increases with increasing engine load in their studies.

Table 5. Exhaust exergy, heat loss exergy and exergy destroyed

	Engine speed [rpm]				
	Exhaust exergy [kW]				
Fuel mixture	1250	1750	2250	2750	3250
D100	1.2	1.499	1.875	2.077	2.307
F20	1.229	1.479	1.799	1.956	2.141
F40	1.234	1.489	1.813	1.965	2.149
Heat loss exergy [kW]					
D100	1.097	1.198	1.406	2.480	2.776
F20	0.815	1.069	1.174	2.408	2.673
F40	0.709	0.933	1.114	2.279	2.521
Exergy destroyed [kW]					
D100	7.173	8.360	10.133	15.438	17.351
F20	5.527	7.263	8.485	14.205	15.848
F40	4.723	6.198	7.590	12.667	14.092

Entropy production varies depending on exergy destruction and environmental temperature. The entropy generation of the D100 fuel at engine speeds of 1250 prm and 3250 rpm is 0.024 kW/K and 0.058 kW/K, respectively. Entropy production is affected by all irreversibilities, especially friction and temperature. As a result of Sanli *et al*. [33] analyses, the entropy production of all fuels was the lowest during this period because the maximum torque occurred at 1800 rpm. The entropy generation for the fuels in the study was found to be 0.16-0.25 kW/K. Thermal and exergy efficiency of fuel blends it is given in tab. 3. In the case where the engine speed is 2250 rpm, the highest thermal and exergy efficiencies have been achieved in all fuel blends. It has been observed that the test engine operates with the highest efficiency at this speed. Thermal efficiency is higher than exergy efficiency at all engine speeds [25-27]. Since the engine power is taken as the same in the calculations of exergy and energy efficiency, it becomes important that the exergy of the fuel is greater than its energy. The difference dec fuel exergy and energy is due to the chemical exergy factor. Since it is usually 1.0-1.5 times the chemical exergy factor in fuels, the fuel exergy will be greater than the fuel energy. The highest energy and exergy efficiency in the study were 28.16% and 34.76%, respectively, in F40 fuel at a speed of 2250 rpm. Dogan *et al.* [25] also calculated the exergy efficiency of pure diesel fuel between 13-15% depending on the engine load in their studies, so it deciderates the results of our study.

Conclusions

In this study, performance and absorption tests of diesel and fueloil fuel blends as fuel at different engine speeds were performed in a compression ignition engine. Exergy and energy analysis were performed using all data are as follows.

- The temperature of the exhaust gases was measured and their exergies were calculated.
- The highest engine power and the lowest fuel consumption in fuel blends were found in F40 fuel. The best results were obtained at 2250 rpm on all fuels in terms of fuel consumption. It was found that this number of revolutions is a suitable value for the operation of the test engine.
- Fuel energies and losses were taken into account in the energy analysis. The highest thermal efficiency was achieved in F40 fuel at 2250 rpm engine speed.
- The entropy production was calculated depending on the exergy destruction and the lowest value was obtained for all engine speeds on F40 fuel.
- Considering the performance, emission and thermodynamic calculations, it was found that the high viscosity of fuel oil can be added to diesel fuel to reduce it.

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