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Energy and Exergy Analysis of Diesel-Hydrogen and Diesel-Ammonia Fuel Blends in Diesel Engine

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Abstract

In response to global warming and pollution, the use of alternative fuels in diesel engines is becoming increasingly important. The purpose of this research is to evaluate the effects of hydrogen and ammonia additions to diesel fuel on carbon emissions and energy and the exergy efficiency of diesel engines and to evaluate sustainability. In this study, the effects of adding 5%, 10%, and 15% of both hydrogen and ammonia to conventional diesel fuel on specific fuel consumption, carbon emissions, energy, exergy, and sustainability index (SI) were examined parametrically. Ammonia and hydrogen fuels reduce CO_2 emissions because they are carbon-free. as a result of the research, it was found that compared with ammonia addition, increasing hydrogen addition lowered specific fuel consumption while decreasing engine performance. The findings obtained show that mechanical energy and exergy values increase by 5.5% in the case of hydrogen addition and decrease by approximately 1.1% in the case of ammonia addition. The thermal efficiency and SI increased in the case of hydrogen addition and decreased in the case of ammonia addition. The exergy efficiency was estimated to be 63.37%, an increase of approximately 2.3% over pure diesel. The highest SI and exergetic performance coefficient values were determined 2.73 and 1.63, respectively. In line with the first and second law analyses, the usability of ammonia and hydrogen in diesel engines was evaluated thermodynamically.

Keywords: Alternative fuels, Exergy analysis, Sustainability index, Hydrogen, Ammonia

1. Introduction

Considering that the use of fossil fuels has significant harmful effects on the natural environment and human life, there are numerous regulations. [1]. In particular, reducing CO_2 due to the greenhouse effect has become extremely important. Approximately 3% of the world's carbon resources come from the maritime sector [2]. The Marine Environment Protection Committee (MEPC 80) aims to reduce greenhouse gas emissions by approximately 40% in 2030 and 70% in 2040, and reach net zero CO_2 emissions by 2050 [3]. Therefore, it is essential to employ alternative fuels or renewable energy sources. To reduce carbon emissions, future engines that use zero-carbon fuels, including hydrogen and ammonia, are being actively developed [4].

Hydrogen is considered a potential fuel because it may function as both a medium for storage and a carrier of energy in fuel cells. Hydrogen can be produced using a few fundamental clean energy sources: sunlight, geothermal power, and biomass gasification. In comparison to geothermal and solar hydrogen, hydrogen produced by the gasification of biomass has a high energy and energetic efficiency [5]. Numerous studies on the use of hydrogen in diesel engines have been published in the literature. Şanlı and Uludamar [6] assessed the energy-exergy efficiency and sustainability index (SI) of diesel and hydrogen-added diesel-biodiesel fuels. Li et al. [7] conducted experiments on a four-cylinder common-rail diesel engine using hydrogen-diesel combustion mode. At 20% and 40% loads, the effects of the amount of hydrogen and fuel injection timing on the combustion efficiency and emission parameters of diesel engines were examined. Duan et al. [8] optimized the combustion properties of a turbocharged direct injection hydrogen diesel engine and their engine performance the entire operating map. Wang et al. [9] compared the

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combustion, injection, and performance of high-energy ignition methods at different ignition energies using computational fluid dynamics. Bayramoğlu and Yılmaz [10] conducted a numerical analysis to investigate how varying injection rates and timings of hydrogen affect the performance of a diesel engine. Bayramoğlu et al. [11] performed a numerical analysis to investigate the impact of varying intake manifold air variable rates and hydrogen addition on the engine performance and emissions parameters of a numerical test diesel engine.

As climate change intensifies, using ammonia as a fuel is considered a reaction to reduce carbon emissions. Because of its auto-ignition, density, and boiling point, ammonia is a fuel that can be used in internal combustion engines [12]. Ammonia has a proven track record as a hydrogen potential carrier and a developed infrastructure for extended distribution and transportation. Ammonia is a suitable green alternative fuel for the decarbonization of diesel engines and power-generating industries because it can be produced using renewable energy sources [13]. Various studies have been conducted on the use of ammonia as fuel. Tian et al. [14] studied the injection strategies of ammonia in internal combustion engines. Qi et al. [15] evaluated the most recent developments in ammonia-hydrogen engines, including ignition methods and combustion techniques, fuel supply, emissions and emission reduction methods. Xu et al. [16] investigated the use of an ammonia diesel mixture in a slow-speed, two-stroke marine diesel engine. Bayramoğlu et al. [17] investigated the effects of methane, hydrogen, and methane, ammonia, and hydrogen combustion combinations on emissions and thermodynamic properties. Pei et al. [18] investigated premixed compression ignition diesel and diesel-piloted engine modes under variable operating parameters to achieve high engine performance and low CO_2 emission in an experimental setup using ammonia-diesel dual fuel. Bani-Hani et al. [19] conducted an energy and exergy analysis of the regenerative Brayton cycle, which uses pentachlorobiphenyl wastes as an alternative fuel. Singh and Paul [20] evaluated the energy, exergy, exhaust emission, exergoeconomic, environmental-economic, and sustainability characteristics of a diesel engine using diesel and pyrolysis oil fuel mixtures. Lin and Wu [21] developed a model to calculate the exergy and energy efficiency of a boiler under various alternative fuel conditions.

The concept of exergy is extremely important in converting the fuel energy used in diesel engines into useful work. In this study, energy, exergy, and sustainability analysis of the use of hydrogen and ammonia fuel in a mixture with diesel fuel was conducted to limit CO_2 emissions against global warming. In contrast to earlier research, this study included analytical balancing equations for the analyses of diesel-hydrogen and diesel ammonia mixtures at 5%, 10%, and 15%. In addition, the change in CO_2 emissions due to the mixture of hydrogen and ammonia was also evaluated in the study.

2. Methodology

The study used a six-cylinder, low-speed marine diesel engine. Table 1 shows the technical specifications of the diesel engine. In general combustion problems, several fuels may be examined together. In a basic combustion problem, the two essential conditions are air and fuel. It is assumed that the combustion products are in balance after combustion. The combustion products and thermodynamic properties depend on the operating parameters, such as temperature and pressure. The diesel-hydrogen and diesel-ammonia combustion processes are given in Equations (1) and (2), respectively [23].

$$xC_\alpha H_\beta + yNH_3 + \frac{a_s}{\emptyset}(O_2 + 3.76N_2) \rightarrow CO_2 + H_2O + O_2 + N_2 + others \quad (1)$$

$$xC_\alpha H_\beta + yH_2 + \frac{a_s}{\emptyset}(O_2 + 3.76N_2) \rightarrow CO_2 + H_2O + O_2 + N_2 + others \quad (2)$$

Table 1. *Specifications of the diesel engine [22]*

Specifications	Unit	Value
Engine type	-	6S35ME
Bore	mm	350
Stroke	mm	1550
Power	kW	5220
SFC	g/kWh	190

In the given equations, is the equivalence ratio, represents the air–fuel stoichiometric ratio, and x and y represent the molar ratios of hydrogen and ammonia, respectively. Table 2 shows the parameters of the diesel, hydrogen, and ammonia used in the study.

Table 2. *Specifications of the investigated fuels [4]*

Specifications	Units	NH3	H_2	Diesel
Storage temperature	K	300	300	300
Lower heating value	MJ/kg	18.5	120	42.7
Adiabatic flame temperature	K	2073	2383	2573
Stoichiometric air-fuel ratio in mass	-	6.05	34.6	14.5

In diesel engines, some of the energy generated by the fuel energy is converted to mechanical power transferred to the propeller, combustion products in the exhaust, and heat transfer to the engine body. The energy balance for the diesel engine can be stated as shown in Equations (3) and (4) using the first law of thermodynamics [24].

$$\dot{E}_{in} = \dot{E}_{out} + \dot{E}_{loss} \tag{3}$$

$$\dot{E}_{fuel} = \dot{E}_{work} + \dot{E}_{exhaust} + \dot{E}_{loss} \tag{4}$$

where $\dot{E}_{fuel}$ is the fuel energy. $\dot{E}_{work}$ is the mechanical power. $\dot{E}_{exhaust}$ is the exhaust energy and $\dot{E}_{loss}$ is the energy loss from the combustion chamber. The energy of the fuel is defined by Equation (5).

$$\dot{E}_{fuel} = \dot{m}_{fuel} \cdot LHV \tag{5}$$

Where, $\dot{m}_{fuel}$ is the fuel mass flow and LHV is the lower heating value of fuel. Combustion products energy in the exhaust is calculated by Equation (6). In exhaust energy calculations, the mass fraction and energy value of each gas in the exhaust are considered.

$$\dot{E}_{exhaust} = \sum \dot{m}_i \cdot \Delta h_i \tag{6}$$

where Δh_i is the enthalpy difference and $\dot{m}_i$ is the mass fraction of the exhaust gasses. The mechanical work and energy loss from the combustion chamber are calculated by Equations (7) and (8), respectively.

$$\dot{E}_{work} = \dot{W} \tag{7}$$

$$\dot{E}_{loss} = \dot{E}_{fuel} + \dot{E}_{air} - \dot{E}_{work} + \dot{E}_{exhaust} \tag{8}$$

Equation (9) can be used to calculate the balance of exergy for a steady-state system [25,26].

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{dest} \tag{9}$$

The exergy balance can be determined using Equation (10) [27].

$$\dot{E}x_{fuel} = \dot{E}x_{work} + \dot{E}x_{exhaust} + \dot{E}x_{loss} + \dot{E}x_{dest} \tag{10}$$

Where, $\dot{E}x_{fuel}$ is the fuel exergy. $\dot{E}x_{work}$ is the mechanical work exergy, $\dot{E}x_{exhaust}$ is the exhaust exergy, $\dot{E}x_{lost}$ is the exergy of the heat loss from combustion chamber and $\dot{E}x_{dest}$ is the exergy destruction. Exergy of fuel can be calculated using Equation (11).

$$\dot{E}x_{fuel} = \dot{m}_{fuel} \cdot LHV \cdot \varepsilon_{fuel} \tag{11}$$

The chemical energy factor ε_{fuel} can be written as Equation (12) [28].

$$\varepsilon_{fuel} = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\frac{\alpha}{C}\left[1 - 2.0628\frac{H}{C}\right] \tag{12}$$

where H, O, C, and S are the mass ratios of hydrogen, oxygen, carbon, and sulfur in the fuel, respectively. Equation (13) can be used to calculate the loss of exergy [29].

$$\dot{E}x_{loss} = \dot{E}_{loss}\left[1 - \frac{T_0}{T_S}\right] \tag{13}$$

Where $\dot{Q}_{loss}$ is the heat transfer from the diesel engine, T_o =300 K is the environmental temperature and T_S is the engine temperature. The exhaust, thermomechanical, and chemical exergy are given by Equations (14), (15), and (16) [30].

$$\dot{E}x_{exhaust} = \sum \dot{m}_i \left(\varepsilon_{ch} + \varepsilon_{thm}\right)_i \tag{14}$$

$$\varepsilon_{ch} = \sum y_i \, E^o{}_{ch} + \bar{R}T_0 \sum y_i \ln\left(y_i\right) \tag{15}$$

$$\varepsilon_{thm} = \sum(h - h_0) - T_0(s - s_0) \tag{16}$$

Where R is the gas constant, y_r is the exhaust gas mole fraction of each product. h is the enthalpy, s is the entropy and T is the temperature. $E^o{}_{ch}$ is the standard chemical exergy [31]. The mechanical exergy can be expressed as Equation (17).

$$\dot{E}x_{work} = \dot{W} \tag{17}$$

The thermodynamic efficiency of the first and second laws are given in Equations (18) and (19) [32].

$$\eta_I = \frac{E_{work}}{E_{fuel}} \tag{18}$$

$$\eta_{II} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{fuel}} \tag{19}$$

Obtaining information on exergy losses in the combustion process depends on the use of another performance criterion known as the exergetic performance coefficient (EPC). Equation (20) is used to calculate the EPC function, which is defined as the ratio of total exergy output to availability loss [33-35].

$$EPC = \frac{\dot{E}x_{fuel} - Ex_{des.}}{Ex_{des.}} \tag{20}$$

The SI is a significant criterion for comparing alternative engine fuels [27]. The SI evaluates the environmental impact of energy systems [36]. The SI can be determined using Equation (21).

$$SI = \frac{1}{1-\eta_{II}} \tag{21}$$

3. Results and Discussion

In addition to conventional diesel fuels, alternative fuels that reduce carbon emissions, such as hydrogen and ammonia, are used in marine diesel engine systems. The first and second laws of thermodynamics and sustainability of 5%, 10%, and 15% hydrogen and ammonia fuel blends are evaluated. In the study, the adiabatic flame temperatures for hydrogen, diesel, and ammonia fuel were taken as 2400 K, 2000 K, and 1600 K, respectively. The exhaust temperatures were calculated by proportioning the adiabatic flame temperature. In addition, for pure combustion values, it has been assumed that hydrogen fuel increases by 25% compared with diesel fuel, while ammonia reduces it by 10% [37]. The combustion process of hydrogen and ammonia added to diesel fuel was performed under the same fuel energy conditions. Figure 1 shows the specific fuel consumption because of 5%, 10%, and 15% hydrogen and ammonia addition to diesel fuel.

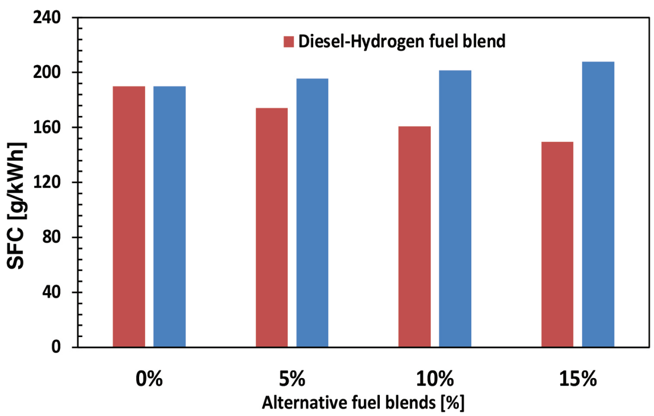

***Figure 1.** Specific fuel consumption of diesel-hydrogen and diesel-ammonia fuel blends*

Considering the calorific values of hydrogen and ammonia, specific fuel consumption decreases as hydrogen addition increases. This is because hydrogen provides more energy per unit mass than diesel. With ammonia addition, specific fuel consumption increases because the lower calorific value of ammonia is less than that of diesel fuel. To provide the same amount of energy, the amount of ammonia per unit energy increase. Carbon emissions have decreased for both hydrogen and ammonia fuels because they are carbon-free fuels. Carbon dioxide emissions for hydrogen and ammonia fuels are shown in Figure 2.

Fuel is injected into the diesel engine to provide approximately 11.7 MW of energy. This energy was assumed to be equal for 5%, 10%, and 15% hydrogen additions and balanced against the amount of fuel. It was determined that there was an increase in the mechanical energy with increasing hydrogen addition. In addition, when the amount of hydrogen added to diesel fuel increased, the exhaust energy decreased. This is due to a decrease in the exhaust flow rate as hydrogen addition increases. In addition, it is observed that mechanical energy increases by 5% for 15% hydrogen addition. Figure 3 shows the diesel engine energy balance for hydrogen addition.

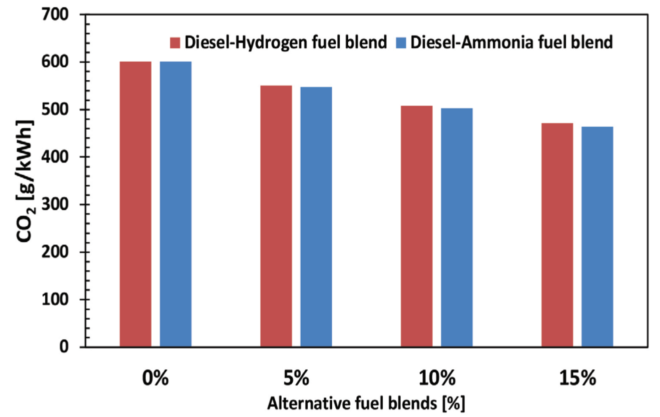

***Figure 2.** CO_2 emissions of diesel-hydrogen and diesel-ammonia fuel blends*

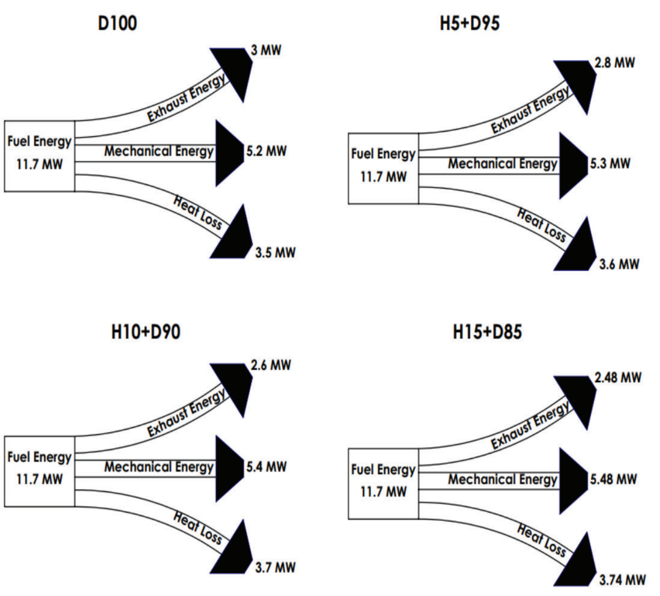

***Figure 3.** Energy balance for diesel-hydrogen blends*

Figure 4 demonstrates the energy balance with the addition of ammonia. Mechanical energy decreased with increasing ammonia addition. The addition of ammonia reduces the combustion chamber temperature of the fuel. The main reason for the decrease in mechanical energy is that ammonia reduces the combustion chamber temperature and pressure. Similar to the addition of hydrogen, the heat

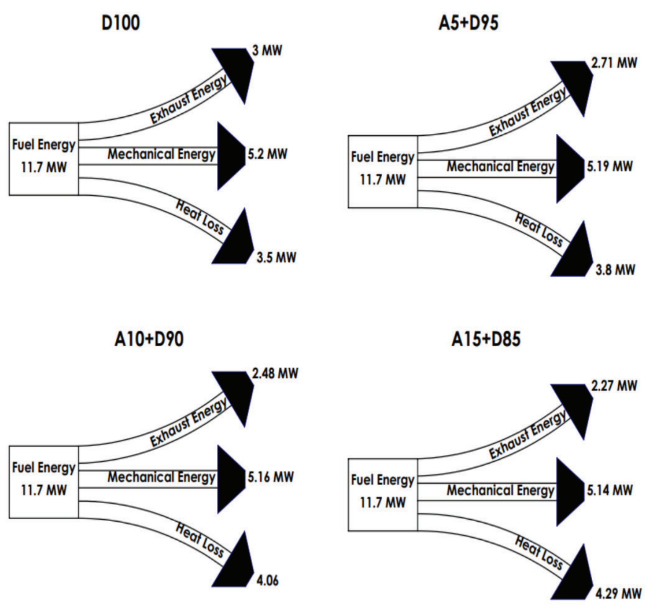

Figure 4. *Energy balance for diesel-ammonia blends*

loss from the combustion chamber also increases with the addition of ammonia.

In diesel engines, fuel exergy is calculated depending on the atomic balance and the lower heating values in the fuel. The fuel exergy determined for the addition of both hydrogen and ammonia to diesel fuel is approximately 12.56 MW. Unlike the concept of energy, exergy destruction is also calculated. Irreversibility, based on the second rule of thermodynamics, causes exergy destruction. It was determined that with increasing hydrogen energy, mechanical exergy and heat exergy increased, whereas exhaust exergy decreased. In addition, exergy destruction accounts for approximately 40% of the total exergy. It can be seen that exergy destruction decreases with increasing hydrogen addition. The exergy balance of diesel-hydrogen addition is shown in Figure 5.

Figure 6 shows the exergy balance for the diesel-ammonia fuel mixture. With increasing ammonia addition, exergy destruction and heat exergy increase, whereas mechanical exergy and exhaust exergy decrease. It can be evaluated that mechanical exergy decreases because of the decrease in engine performance of ammonia addition. This can also be explained by the fact that ammonia increases irreversibility and exergy destruction.

Thermal efficiency values calculated using the first law of thermodynamics and the second law of exergy efficiency for diesel-hydrogen and diesel-ammonia fuel blends are shown in Figure 7. It was determined that the thermal efficiency increased with increasing hydrogen addition and decreased with increasing ammonia. Thermal efficiency increases by approximately 5% for 15% hydrogen addition. It was determined that in the case of 15% ammonia addition, the thermal efficiency decreased by 1.5%. The findings show that the highest thermal efficiency is in the 15% diesel-hydrogen blends and the lowest thermal efficiency is in the 15% diesel-ammonia blends. When the second law efficiencies are compared, in the case of 15% hydrogen addition, the exergy efficiency was determined to be

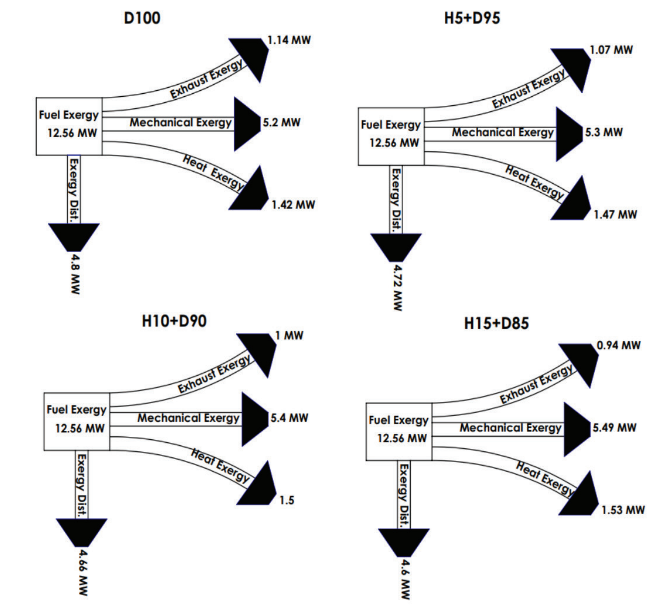

Figure 5. *Exergy balance for diesel-hydrogen blends*

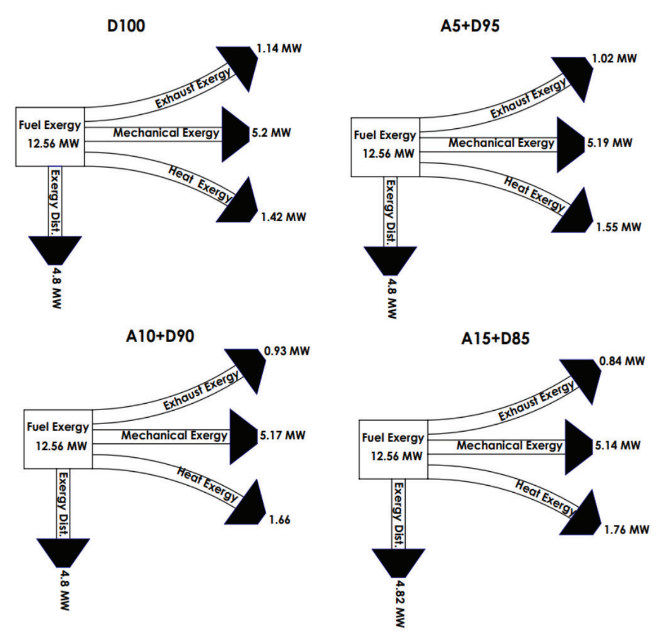

Figure 6. *Energy balance for diesel-ammonia blends*

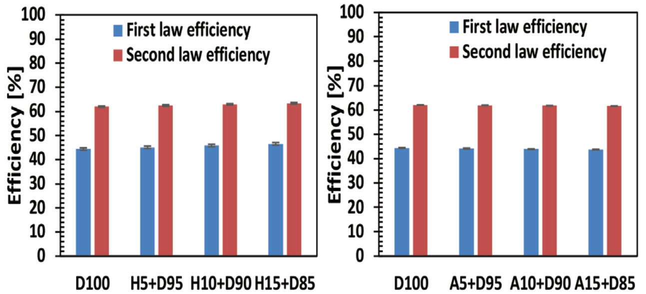

Figure 7. *First and second law efficiency*

63.37%, an increase of approximately 2.3% compared with the use of pure diesel. With 15% ammonia addition, the exergy efficiency was 61.62%.

Figure 8 shows the model findings according to the EPC criteria. Determining the ecological performance of combustion processes and comparing the findings with second-law characteristics are essential technical parameters. The findings show that the EPC value in diesel combustion is approximately 1.63. It was observed that in the case of 15% hydrogen addition, the EPC value was approximately 1.73, and in the case of 15% ammonia addition, the EPC value was 1.63.

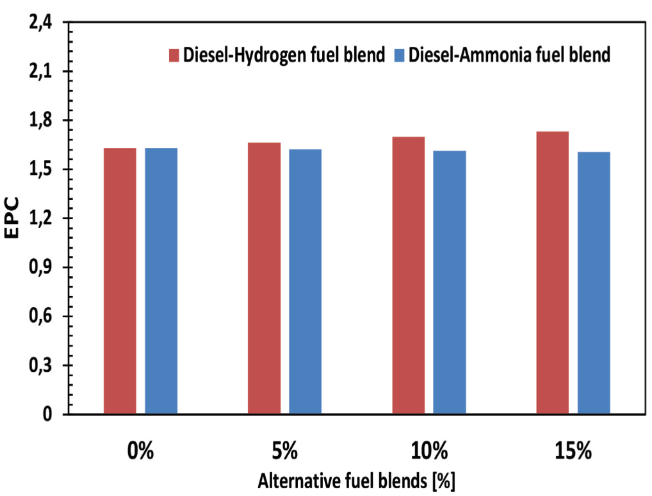

Figure 8. *Variations in EPC*

EPC: Exergetic performance coefficient

Figure 9 demonstrates the SI, which is a derivative of the second law for hydrogen and ammonia addition. Based on exergy data, it was determined that diesel-hydrogen addition increased the SI, whereas ammonia-diesel addition decreased the SI. The SI was determined to be approximately 2.73 for 15% hydrogen addition and approximately 2.6 for 15% ammonia addition.

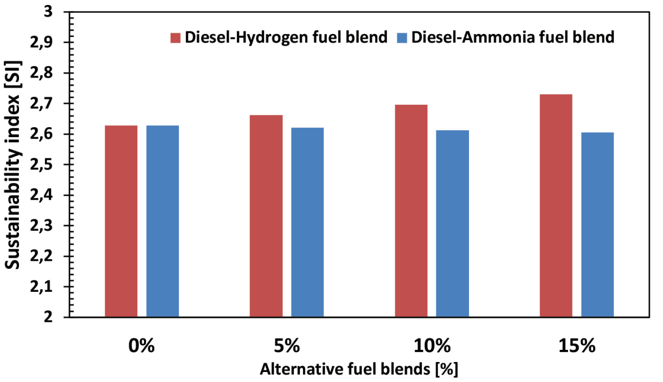

Figure 9. *Sustainability index*

4. Conclusion

This study investigated the effects of 5%, 10%, and 15% hydrogen and 5%, 10%, and 15% ammonia to conventional diesel fuel on energy, exergy, and carbon emissions. The model includes analytical evaluation of the energy and exergy impact of hydrogen and ammonia additions based on fuel consumption under the same fuel energy conditions. With the investigation, the following main findings were obtained:

- Specific fuel consumption was determined under the same fuel energy conditions according to the lower calorific values of the fuels used. It has been determined that 15% hydrogen addition reduces specific fuel consumption by approximately 21%, whereas 15% ammonia addition increases it by 9.5%.
- The main reason why hydrogen and ammonia fuels will be preferred in the future is that they are carbon-free. Therefore, it was determined that carbon emissions decreased for both fuels. It has been observed that carbon emissions per hour are lower because hydrogen fuel reduces engine fuel consumption.
- Energy efficiency is higher with hydrogen fuel addition. Therefore, the mechanical energy increase was determined to be higher in the case of hydrogen addition. In a 15% diesel-hydrogen blend, mechanical energy increased by 5%. For the 15% diesel-ammonia blend, mechanical energy decreased by 1.1%.
- In exergy balance, while exergy destruction increased in the diesel-ammonia mixture, it decreased in the diesel-hydrogen mixture. Mechanical exergy increases with the addition of hydrogen and decreases with the addition of ammonia, depending on the mechanical energy.
- The thermal efficiency, which is the first law energy, was determined to be approximately 46.59% with 15% hydrogen addition. It was determined to be 43.71% in 15%

ammonia addition. The second law efficiency is 63.37% with 15% hydrogen addition and 61.62% with 15% ammonia addition. The SI increases with the addition of hydrogen and decreases with the addition of ammonia.

• In this study, SI and EPC calculations were carried out. The SI was calculated to be approximately 2.73 for 15% hydrogen addition and 2.6 for 15% ammonia addition. The results indicate that the EPC value for diesel combustion is approximately 1.63. The EPC value for 15% hydrogen addition was around 1.73, whereas that for 15% ammonia addition was around 1.63.

In future studies, LCA guidelines, and wake-up well calculations, including well-to-tank and tank-to-wake emission factors, could be analyzed for the impact on carbon emissions of ammonia and hydrogen fuels used as alternative fuels. Additionally, energy, exergy, and sustainability analyses of alcohol and biodiesel fuels can be performed as alternative fuels.

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