International Journal of Hydrogen Energy 137 (2025) 679–688

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Compression ignition engine performance and emissions: An experimental study on the impact of aqueous ammonia, hydrogen, and diesel fuel blends

Mehmet Sarıtaş *, Volkan Sabri Kül, Selahaddin Orhan Akansu, Happy Sinkala

Erciyes University, Graduate School of Natural and Applied Sciences, (Department of Mechanical Engineering), Kayseri, Türkiye

ARTICLE INFO

Handling Editor: Prof. J. W. Sheffield

Keywords:
Aqueous ammonia
Diesel
Hydrogen
Emissions
Performance

ABSTRACT

In this study, experiments are carried out using aqueous ammonia, hydrogen, and diesel fuels in a compression ignition engine. A heavy-duty diesel engine with a cylinder volume of 11 L is used as the test engine. Experiments are conducted at four different torque levels: 25 %, 50 %, 75 %, and 100 %, where 300 Nm represents full load. The engine operates at a constant speed of 660 rpm. Initially, neat diesel is used, followed by blends containing 10 wt% and 20 wt% aqueous ammonia. Hydrogen is also added through the intake manifold at 1 bar pressure, supplying 10 % of the total energy content of each mixture. Aqueous ammonia addition increases in-cylinder pressure and improves thermal efficiency. The highest thermal efficiency is observed with A20D80 (20 wt% ammonium hydroxide) at 39.18 %. Thermal efficiencies for A10D90, A10D90H10, A20D80H10, D100, and D100H are 34.26 %, 32.83 %, 31.67 %, 29.21 %, and 28.34 %, respectively.

Nomenclature

AVS	Ammonia Volume Share	**AFR**	Air-Fuel Ratio
BSFC	Brake Specific Fuel Consumption	**Rpm**	Revolutions Per Minute
VVT	Variable Valve Timing	**Ppm**	Parts Per Million
DDF	Diesel-Double Fuel	**L**	Liters
CO	Carbon Monoxide	**Nm**	Newton Meter
NOx	Nitric Oxides	**BMEP**	Brake Mean Effective Pressure
K	Kelvin	**NH_4OH**	Ammonium Hydroxide
CAD	Crank Angle Degree	**1D**	One-Dimensional
ICP	In-Cylinder Pressure	**Mm**	Milimeter
KI	Knock Index	**Cc**	Cubic Centimeters
MPa	Megapascal	**BTDC**	Before Top Dead Center
CA	Crank Angle	**Hp**	Horse Power
BTE	Brake Thermal Efficiency	**m^3**	Cubic Metres
LPM	Liter Per Minute	**°C**	Celsius
TiO_2	Titanium Dioxide	**Kg**	kilogram
NH_3	Ammonia	**Mj**	Megajoules
CO2	Carbon Dioxide	**App.**	Approximately
H_2	Hydrogen	**LHV**	Low Heat Value
HC	Unburned Hydrocarbons	**G**	gram
wt%	Percentage by weight	**TDC**	Top Dead Center

1. Introduction

Global population growth and industrial activities have led to a significant increase in energy demand recently. This has led to concerns about energy security and environmental sustainability. Diesel engines using diesel fuel are still widely used in transportation and heavy-duty applications due to their high thermal efficiency and fuel economy, and optimizing and reducing their emissions has become the focus of efforts to address current energy challenges [1]. The high consumption of fossil fuels leads to a depletion of energy resources and creates a high accumulation of greenhouse gases in the atmosphere. This leads to global climate change. Vehicles and machinery using internal combustion engines account for a significant amount of the use of fossil fuels. Since such engines are widely used, the demand for fossil fuels is increasing. The number of vehicles using internal combustion engines is expected to increase in the future, thus putting significant pressure on the use of fossil fuels [2,3]. Given the limited availability of fossil fuels, the widespread adoption of alternative fuels and renewable sources is necessary. To produce alternative fuels for diesel engines, various chemical compounds have been blended with pure diesel in specific ratios to create alternative fuel mixtures. Wang et al. examined engine performance by mixing ammonia and hydrogen in certain proportions.

This article is part of a special issue entitled: ICEESEN-2024 (Akansu) published in International Journal of Hydrogen Energy.

* Corresponding author.
E-mail addresses: mehmetsaritas@erciyes.edu.tr (M. Sarıtaş), volkanskul@gmail.com (V.S. Kül), akansu@erciyes.edu.tr (S.O. Akansu), hapsink@gmail.com (H. Sinkala).

https://doi.org/10.1016/j.ijhydene.2025.05.121
Received 3 March 2025; Received in revised form 7 May 2025; Accepted 8 May 2025
0360-3199/© 2025 Hydrogen Energy Publications LLC. Published by Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

They reported that the best results were achieved with a 30 % hydrogen blend. This application resulted in increased in-cylinder pressure (ICP) and power while reducing fuel consumption rates. However, an increase in NOx emissions was observed due to the use of nitrogen [4]. Qian et al. investigated the effect of hydrogen in an ammonia-diesel dual-fuel mode, using a method where hydrogen was mixed at an energy ratio of 10 % at each engine speed. The diesel energy was fixed at 45 %. The addition of hydrogen increases the engine's heat release and pressure, reduces particulate emissions, but increases NOx emissions. At low loads, the effect of hydrogen diminishes; however, with appropriate heating, ammonia emissions can be significantly reduced [5]. Bayramoğlu K., the effects of ammonia and hydrogen addition to diesel fuel on fuel consumption, emissions, and energy efficiency were investigated using energy-based ratios of these fuels (5 %, 10 %, and 15 %). It was shown that the addition of hydrogen at a 15 % energy ratio reduced total fuel consumption by 21 %, and the addition of ammonia at a 15 % energy ratio increased fuel consumption. Hydrogen increased energy efficiency; ammonia decreased it. Since both fuels are carbon-free, CO_2 emissions were reduced, but the reduction in CO_2 emissions was more pronounced with hydrogen [6]. In another study, different amounts of hydrogen were added to a 4-cylinder water-cooled diesel engine, and engine performance and emissions were investigated at different loads (from 20 % to 100 %) and at a constant speed of 1800 rpm. Hydrogen addition increased BSFC (brake specific fuel consumption) and BTE (brake thermal efficiency) at all loads, especially at high hydrogen additions and high loads; an increase in exhaust temperature and NO_x emissions was observed. Significant reductions in emissions such as HC and CO were also recorded. The use of hydrogen in diesel engines has been shown to reduce emissions and improve performance. However, this increase in NOx emissions requires optimization of such applications. These findings suggest that the use of hydrogen as an alternative in diesel engines has both advantages and disadvantages [7]. Ammonia is attracting more and more attention as a carbon-free fuel alternative. It is a green fuel in terms of CO and CO_2 emissions because it is easy to store, stored as a liquid at atmospheric pressure, and does not produce carbon-based emissions. Nadimi et al. tested the effects of using ammonia and diesel fuel in dual fuel mode on emissions and engine performance. In addition, a 1D model was used to analyze the combustion characteristics of ammonia and diesel fuel. Ammonia provided 84.2 % of the energy required by the engine. As the ammonia content increases, the thermal efficiency also increases. However, as the use of ammonia increases, the combustion timing also changes. A slower combustion is obtained when using pure diesel. When an ammonia-diesel mixture is used, a faster combustion occurs. This shortened the combustion time by 6.8 CAD and the combustion phase by 32 CAD. The use of ammonia reduces carbon-based emissions but increases NO_x emissions and the amount of unburned ammonia (14,800 ppm). Nitrous oxide is released during combustion and offsets the reduction in CO_2 emissions. Therefore, in order to reduce emissions, at least 35,9 % ammonia-diesel mixture should be used in diesel fuel [8]. Since hydrogen and ammonia have complementary properties in terms of combustion characteristics, it is a logical approach to use them together. Therefore, load control strategies in a hydrogen-ammonia dual-fueled system were investigated, and strategies such as ammonia volume share (AVS) modification, qualitative control, quantitative control, and intake variable valve timing (VVT) adjustment were evaluated. Thermal efficiency was improved by using the Miller cycle, and the engine was able to achieve higher mean effective pressure (BMEP) and thermal efficiency (BTE) by changing the AVS values [9]. Alternatively, similar objectives have been sought using fuel additives. For example, by adding aluminum particles to diesel fuel, the combustion process has been improved, and both efficiency and NOx, CO, and HC emissions have been reduced [10]. Both of these methods have shown promise in improving the performance and reducing the environmental impact of diesel engines [9,10]. Ammonia and water vapor is another alternative fuel duo. The effects of these fuels and additives on engine performance and emissions have also been studied in detail. For example, in one study, different concentrations of ammonia-water solution (NH_4OH) were sprayed from the engine intake manifold into the cylinder and delivered to the combustion chamber as cold vapor. In experiments using aqueous ammonia with ammonia concentration ratios of 5 %–10 %-15 %, it was observed that engine efficiency was adversely affected as the amount of ammonia increased. Compared to the thermal efficiency (BTE) of pure diesel fuel, especially when 100 % torque is applied, the efficiencies decreased by 0.09 %, 2.27 %, and 3.57 % with the addition of 5 %–10 % and 15 % ammonia, respectively. In the experiments using pure water, the thermal efficiency increased significantly as the torque ratio increased. However, the thermal fuel efficiency of pure diesel could not be reached. On the other hand, water vapor was observed to improve NO and HC emissions. As the ammonia concentration increases, NO_x emissions increase at low and medium loads. When 100 % torque was applied, NO_x emissions decreased relatively as the ammonia concentration increased. The highest NO_x values were obtained in experiments with 15 % NH_4OH. However, Nox emission values were lower than pure diesel fuel in experiments with aqueous ammonia addition at 100 % torque. These findings reveal the complex effects of alternatives such as ammonia and water vapor in terms of engine performance and emissions [11].

Regarding the synergies of the use of the ammonia-hydrogen dual fuels, carbon-free fuels play a key role in the production of carbon-based emissions. While ammonia has advantages over hydrogen in terms of hydrogen carrying capacity, ease of storage and transport, ammonia's combustion inertness creates some difficulties in its application, and the combustion process needs to be improved to overcome these difficulties. Hydrogen, as a carbon-free and highly reactive fuel, can be used as a powerful combustion promoter that maximizes the carbon-free effect of ammonia. Ammonia-hydrogen synergistic combustion further improves overall energy efficiency, especially when combined with hybrid power systems [12].

Tsujimara et al. conducted a study aiming to develop hydrogen combustion technologies that provide high efficiency and low emissions. In this study, especially diesel-double fuel (DDF) combustion technology was mentioned. It uses diesel fuel and hydrogen fuel at the same time. However, due to the high flammability of hydrogen, difficult situations such as abnormal combustion, dirty emissions, and low thermal efficiency are encountered in DDF engines. In this study, a single-cylinder diesel engine with gas injectors installed in the intake manifold is used. DDF engine performance was investigated with variables such as hydrogen injection amount, engine speed, and engine load. The experiments indicate that the use of hydrogen DDF at high engine loads is more efficient than the use of conventional diesel. Pre-ignition occurred at high hydrogen energy ratios, and this limited the amount of hydrogen that could be injected. In addition, the relationship between ignition chamber temperature and pre-ignition was analyzed to understand the limitations of hydrogen DDF engines [13].

Another study reinforces that fuels should be used in pairs in order to eliminate the disadvantages they cause when used separately. It was mentioned that the ignition and combustion performance of ammonia fuel is poor and the auto-ignition temperature is high. To overcome such difficulties, mixing with hydrogen fuel was considered to be the right way. In addition, it was tried to create a better combustion by increasing the intake air temperature. The effects of ammonia/hydrogen mixture ratios on engine combustion and emissions at different intake temperatures were investigated. Engine performance and emissions were investigated at four different intake temperatures ranging from 476K to 551K using 0 %–90 % ammonia-hydrogen mixture ratios. The results showed that at 476 K intake temperature and 30 % hydrogen mixture ratio, the engine power was the highest and the KI value (knock index) was slightly above 2 MPa/CA. Under these conditions, the negative engine operation was reduced, and the overall engine performance was at its best. Ammonia fugitive emissions were eliminated, and emissions improved. With these results, the hydrogen/ammonia blend has proved

to be one of the best ways to achieve the zero carbon emission target [14].

The use of biodiesel in combination with hydrogen and ammonia was investigated in a single cylinder diesel engine. A mixture of 10 % biodiesel with 10 LPM hydrogen and 10 LPM ammonia was used as fuel. The effects of the blends on BTE, BSFC, and emissions were observed. The use of 20 % biodiesel-diesel blends resulted in a decrease in brake thermal efficiency due to high heat of vaporization. The addition of hydrogen and ammonia improved combustion, and a significant increase in BTE was observed. The addition of TiO_2 nanoparticles to this fuel mixture caused variable effects at different loads, and BSFC decreased with the addition of ammonia and hydrogen. Although an increase in NOx emissions was observed, carbon emissions (HC, CO) decreased due to the use of ammonia, a carbon-free fuel. With these results, the use of hydrogen with ammonia and biodiesel offers benefits for both engine performance and the production of an environmentally friendly engine [15].

In a study involving the use of ammonia and hydrogen gases as a dual fuel, a series of tests were carried out using different amounts of hydrogen and ammonia. In particular, the S4 blend with high hydrogen content (10 LPM NH_3 gas and 10 LPM hydrogen gas) improved the brake thermal efficiency (BTE), resulting in a better efficiency compared to pure diesel fuel. Nox emissions increased due to the high temperatures generated during the combustion process, but this increase was offset by reducing flame temperatures by using ammonia and hydrogen together [16].

This study aimed to reduce the negative effects of fossil fuels and increase thermal efficiency. For this purpose, ammonium hydroxide (25 % purity NH_4OH) was added to pure diesel at varying ratios (10 % increments between 0 % and 20 %), and 10 % hydrogen gas was added from the intake manifold in terms of energy ratio, and the mixture was formed. Engine performance and exhaust emissions were measured at constant engine speed (660 RPM) in increments of (75 Nm, 150 Nm, 225 Nm, and 300 Nm) up to 300 Nm, the maximum torque of the engine. These results were compared with tests using neat diesel under the same experimental conditions.

Wang et al. [4] investigated the effects of a mixture of different proportions of ammonia and hydrogen gases on combustion characteristics at 1800 rpm in a diesel engine. According to the results obtained, engine power increased due to the increase in the hydrogen ratio in the mixture. They reported that NOx emissions increased with the increase in the hydrogen ratio in the mixture due to the high combustion temperature of hydrogen. On the other hand, they stated that improvements were observed in CO and HC emissions. Frost et al. [31] investigated the changes in engine performance and emissions by injecting NH4OH at different aspiration degrees from the intake manifold at different engine loads in a compression ignition engine. They stated that the ignition delay increased with the increase in the amount of aqueous ammonia injection. As a result, the in-cylinder peak pressure increased, but they reported a general decrease in combustion quality. A decrease in NOx emissions was observed as the amount of aqueous ammonia (NH4OH) injection increased. They attributed this to the instability of combustion due to high NH4OH aspiration and therefore combustion at lower temperatures. Duraisamy et al. [32] injected hydrogen into the engine through the engine intake manifold at flow rates ranging from 25 to 10 lpm in order to increase the performance of biodiesel and reduce emissions. As a result of the experiments conducted with the fuel mixture formed by adding 20 % biodiesel (D20) to diesel fuel and hydrogen injection, they reported that HC, CO and smoke emissions decreased. On the other hand, they observed that NOx emissions increased due to the high combustion temperature of hydrogen. They also reported that hydrogen injection at engine start-up with D20 fuel provided an increase in BTE. Al-Dawody et al. [33] conducted their studies by adding 40, 50 and 60 % NH4OH to diesel fuel. They stated that aqueous ammonia reduced engine efficiency. They observed a significant decrease in NOx emissions. Kül et al. [11] carried out experiments at 660 rpm engine speed and 25, 50 and 100 % engine loads by adding NH4OH containing 5, 10 and 15 % NH3 to diesel fuel. In these experiments, they investigated the changes in engine performance and exhaust emissions. They determined that there was a decrease in BTE due to the increase in NH3 ratio in aqueous ammonia. The decrease in BTE was 0.09, 2.27 and 3.57 % for NH4OH containing 5, 10 and 15 % NH3, respectively. The addition of aqueous ammonia to diesel fuel generally increased HC, CO and CO2 emissions. They stated that NOx emissions increased at 25 and 50 % engine loads, while they relatively decreased at 100 % engine load.

The main objective of the study is to fill the gap in the literature by analyzing in detail the effects of ammonia (ammonium hydroxide), hydrogen gas (H_2), and diesel fuel mixtures dissolved 25 % in water on engine performance and exhaust emissions. While ammonia improves combustion characteristics, hydrogen gas is intended to minimise the increase in Nox emissions due to its high energy content and clean combustion advantages. This approach offers a promising solution for improving thermal efficiency as well as reducing the environmental impact of fossil fuels.

2. Material and methods

2.1. Experimental setup and equipment

In this study, the experimental setup consists of a 6-cylinder compression ignition diesel engine, "PCS'' brands performance measurement system, Bosch BEA60 emission analyzer, 200 bar pressure hydrogen cylinder, hydrogen pressure regulator, precision scale for measuring liquid fuel consumption and in-cylinder pressure measurement system. The test engine and its technical specifications are shown in Fig. 1 and Table 1. The injection strategies of the fuels are as follows: a mixture of NH4OH and diesel fuels is mixed throughout the test by means of a magnetic stirrer and stands on a scale. This mixture is injected into the cylinders of the internal combustion engine via a fuel line. When the mixture containing hydrogen is desired to be used, liquid fuels are withdrawn from the fuel line while at the same time the hydrogen gas in the 200 bar cylinders is reduced to 1 bar using the pressure regulator "ALICAT'' brand and given through the intake manifold of the engine. "ALICAT'' technical specifications are presented in Table 3. This regulator allows for an inlet pressure of 1–230 bar and an adjustable outlet pressure ranging from 1 to 10 bar. The temperature at which it operates ranges from −20 to +70° Celsius. The gas is suffocated by the regulator, which lowers the pressure from 200 bar to 1 bar. This suffocation gas expands past the regulator, resulting in a pressure drop and a change in temperature of the gases experiencing this pressure reduction. The Joule-Thomson coefficient refers to the ratio of

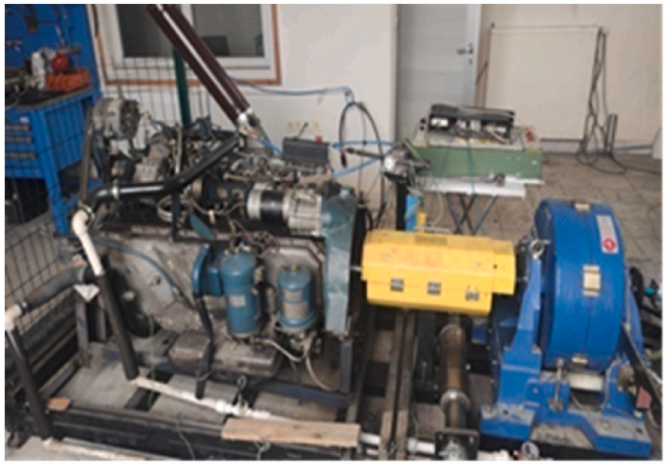


Fig. 1. Test Engine-HDV.

Table 1
Test Engine-HDV technical specifications [1].

Test engine	NİSSAN PE6H
Bore and Stroke.	133 mm, 140 mm
Displaced volume	11,670 cc
Max. Power and speed	234 Hp, 2300 rpm
Compression ratio	16.5
Injection timing	16 ‘BTDC

Table 2
Gas Regulator Properties [29].

Material	Yellow alloy of copper and zinc
Inlet and Outlet Ports	DN20
Inlet Pressure	0–230 bar
Outlet Pressure	0–10 bar
Diaphragm and Seals	Mebran
Operating Temperature Range	(-20 °C) - (+70 °C)
Dome Loading Port	M16x1,5
Layers	2
Inner Diameter	6,5 mm

Table 3
ALICAT flow controller technical specifications [29].

Accuracy	± (% 0,8 reading + % 0,2)
Repeatability	± % 0,2
Operating range	200:1
Maximum controllable flow rate	%102,4
Maximum measurable flow rate full scale	%128
Response time	100 ms (Adjustable)
Warm-up time	<1 s
Operating temperature	−10 °C/+60 °C
Humidity range (Non-condensing)	%0 - %100
Maximum internal pressure (Static)	145 psi
Test pressure	175 psi
Valve type	Normally closed

temperature change to pressure change in pressure reduction processes [10]. Gas regulator properties are given in Table 2. An eddy current dynamometer was employed to measure the engine’s torque and power output. Engine speed was recorded using an encoder with a sensitivity of 1/360°. In-cylinder pressure measurements were obtained via a piezo-electric sensor. The experimental setup and the equipment used are illustrated in Fig. 2.

2.2. Fuel preparation

The codes of the blended fuels are presented in Table 5 and fuel properties are presented in Table 6. Pure diesel, 25 % purity aqueous ammonia solution (NH_4OH), and hydrogen were used as test fuels in the experiments. The experiments without hydrogen were designated as D100, A10D90, and A20D80, respectively. Of these codes, D100 represents pure diesel, A10D90 represents 10 wt % NH4OH aqueous ammonia and 90 wt% diesel, and A20D80 represents diesel with 20 wt % NH_4OH aqueous ammonia (aqueous ammonia added to diesel contains 25 % NH_3). Hydrogen was then added to the experiments with these three fuels, corresponding to 10 % of the energy consumption data. These fuels are coded as D100H10, A10D90H10, and A20D80H10, respectively. This means that D100H10 fuel contains pure diesel. This is the addition of hydrogen fuel that can produce 10 % of the energy that pure diesel can produce. (These calculations are based on LHV values). A10D90H10 fuel contains 10 % by weight of NH_4OH and 90 % by weight of diesel. A10D90H10 fuel is obtained by adding hydrogen in an amount that can produce 10 % of the energy that the A10D90 liquid mixture can produce. (These calculations are based on LHV values.) In the same way, A20D80H10 fuel contains 20 % by weight of NH_4OH and 80 % by weight of diesel. A20D80H10 fuel is obtained by adding hydrogen in an amount that can produce 10 % of the energy that the A20D80 liquid mixture can produce. (These calculations are based on LHV values.) Liquid fuels (NH_4OH and diesel) were mixed outside using a magnetic stirrer and added to the fuel tank. When it was necessary to add hydrogen in addition to liquid fuels, hydrogen gas was added from the intake manifold independently from the liquid fuel line.

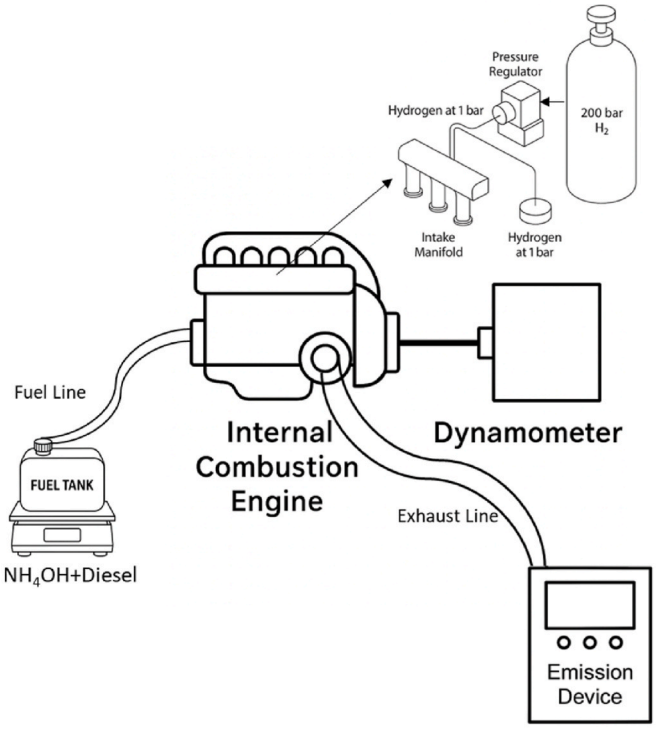


Fig. 2. Schematic representation of the test setup.

Table 4
Key safety measures for 25 % NH_4OH based on MSDS guidelines.

Category	Precaution/Description
Hazard Identification	Causes skin/eye irritation; harmful if inhaled; strong pungent odor
First-Aid Measures	Eyes: Rinse with water for 15 min; Inhalation: Move to fresh air, seek medical attention
Handling & Storage	Store tightly closed, in a cool, ventilated area away from acids
Personal Protection (PPE)	Use safety goggles, nitrile gloves, lab coat, and operate under fume hood
Accidental Release Measures	Ventilate area; absorb with inert material; avoid discharge to drains
Physical and Chemical Props.	Colorless liquid, pH > 11, strong ammonia odor

Table 5
Codes of blended fuels.

Code	Mixture Composition
D100	Pure Diesel
A10D90	90 % Diesel and 10 % Aqueous Ammonia (NH_4OH).
A20D80	80 % Diesel and 20 % Aqueous Ammonia (NH_4OH).
D100H10	100 % Diesel and 10 % Hydrogen (H_2)
A10D90H10	90 % Diesel, 10 % Hydrogen (H_2), and 10 % Aqueous Ammonia (NH_4OH).
A20D80H10	80 % Diesel, 10 % Hydrogen (H_2), and 20 % Aqueous Ammonia (NH_4OH).

Table 6
Specifications of fuels.

Property	Ammonium Hydroxide 25 %	Diesel	Hydrogen
Chemical Formula	NH_4OH (25 % NH_3 in water)	C_nH_{2n} (hydrocarbon mixture)	H_2
Density (15–20 °C)	0.91–0.92 g/cm^3	0.83–0.85 g/cm^3	0.08988 g/L (at STP)
Boiling Point	~37 °C	180–360 °C	−252.9 °C
Flash Point	No flammable vapor (aqueous)	≥52 °C	−253 °C
Lower Heating Value (LHV)	4.65 MJ/kg	~42–45 MJ/kg	~120 MJ/kg
Sulfur Content	None	≤15 ppm (ULSD)	None
Cetane Number	Not applicable	≥40	Not applicable
Viscosity (at 40 °C)	Similar to water (~1 cSt)	1.9–4.1 mm^2/s	Not applicable (gas)
pH (at 25 °C)	11.6–12.4	N/A	N/A
Corrosion Potential	High (especially with Cu, Al, Zn)	Moderate (Copper Strip ≤ No. 3)	None (inert gas)
ASTM Standard	ASTM D511	ASTM D975	ASTM D7265
Application Area	NOx control, industrial cleaning, fuel blending	Engines, generators, transport	Fuel cells, combustion engines, aerospace

2.2.1. Safety precautions and warnings for the use of aqueous ammonium hydroxide (25 %)

Aqueous ammonium hydroxide (25 % NH_4OH solution) was used as an ammonia source. It is less volatile than gaseous ammonia (NH_3) and safe to work with under laboratory conditions. All procedures involving NH_4OH were carried out in accordance with the MSDS (Material Safety Data Sheet). Half-face gas mask with the EN 140 standard, protective goggle, proper ventilation, and safe storage practices were ensured. Key Safety Precautions for 25 % NH_4OH based on MSDS Guidelines are given in Table 4.

Fuel consumption measurement utilized the precision scale of the DESIS-KF-H2W model. It has a sensitivity of 0.5 g. In each experimental set, fuel consumption was documented at 2-min intervals. The amount of fuel consumed was determined by calculating the difference in mass between the beginning and end of the consumption period.

3. Results and discussion

3.1. Engine performance

Brake thermal efficiency is calculated by dividing the engine's brake power by the amount of fuel consumed and the fuel's lower heating value [17].

$$\eta_{th} = \frac{P_b}{\dot{m}_f \times LHV} \tag{1}$$

P_b : *braking power*
$\dot{m}_f$: *fuel mass flow rate*
LHV : *the lower heating value of the fuel*

For the mixture, the LHV value is determined using Equation (2).

$$LHV_K = \frac{m_b \times LHV_b + m_m \times LHV_m}{m_b + m_m} \tag{2}$$

m_b : *amount of first fuel*
m_m : *amount of second fuel*
LHV_b : *lower heat value of the first fuel*
LHV_m : *lower heat value of the second fuel*

Hydrogen is supplied to the system from the intake manifold in the test system. This caused the hydrogen to replace the air and the air excess coefficient to increase and therefore the equivalence ratio to decrease [30].

$$\lambda = \frac{AFR_{(actual)}}{AFR_{(stoichiometric)}} \tag{3}$$

$$\Phi = \frac{1}{\lambda} \tag{4}$$

Since the system has to work with less air to produce the same amount of power, it has to consume more fuel, and efficiency has decreased. Table 7 given below shows the equivalence ratio differences between D100 and D100H10, A10D90 and A10D90H10, and A20D80 and A20D80H10 fuels under a 300 Nm load. This is one of the reasons for the decrease in efficiency.

Another reason for the decrease in efficiency is that the density of hydrogen is lower than that of air, so it occupies more volume, and this reduces the volumetric efficiency, which is one of the reasons for the decrease in BTE.

The graph given in Fig. 3 was drawn using the data found in the experiment and the equations given above. In order to understand the effect of hydrogen, it is necessary to follow the Diesel-Diesel/H2 lines (blue and orange lines). The use of hydrogen at a 10 % energy ratio has a negative effect on brake thermal efficiency at all loads. The high auto-ignition temperature of hydrogen caused ignition delay, which negatively affected the combustion process. Therefore, thermal efficiency decreased. The study by Zhang et al. supports this [22]. By looking at Diesel-D90A10 and Diesel-D80A20 lines dark blue-dark green and dark blue-violet), it can be understood that ammonium hydroxide increases brake efficiency (BTE) at 40 % and above loads. The highest BTE was obtained from the D80A20 mixture. The D80A20 blend is about 34.12 % more efficient than pure diesel and about 14.35 % more efficient than the D90A10 blend. These results were made possible by ammonia, which makes the combustion process more stable and improves combustion efficiency. Ammonia stabilized the in-cylinder temperature during combustion and optimized the combustion reactions [24,25]. Thanks to the components contained in ammonium hydroxide, it decomposes into water vapor and ammonia during combustion. The water vapor it forms not only reduces the temperature in the cylinder by absorbing heat through its latent heat of vaporization. Additionally, it improves knock resistance and helps to smoothen the pressure rise rate. Ammonia also participates as a slow-reacting fuel, which extends the combustion duration, improves the oxidation completeness, and enhances overall thermal efficiency. These results proved the potential of ammonia to improve combustion stability, reduce emissions, and increase thermal efficiency, consistent with studies found in the literature [26,27].

Fig. 4 presents the cylinder pressure graph under a 300 Nm load. This graph can be evaluated from four different perspectives. Firstly, the addition of 10 % hydrogen to the diesel fuel resulted in a 1.72 % reduction in the maximum cylinder pressure. Additionally, it caused an approximate 1 CA ignition delay. The addition of hydrogen to diesel fuel can significantly reduce the overall fuel/air equivalence ratio, extend the ignition delay, and adversely affect combustion quality. This situation may lead to a decrease in the maximum cylinder pressure [18]. Secondly, under a constant hydrogen ratio of 10 %, focusing on the

Table 7
Air excess coefficient and equivalence ratio of fuels.

Fuels	Air Excess Coefficient (λ)	Equivalence Ratio (1/λ)
D100	2,502	0,400
D100H10	2,586	0,387
A10D90	2,84	0,352
A10D90H10	3,093	0,323
A20D80	2,901	0,345
A20D80H10	3,051	0,328

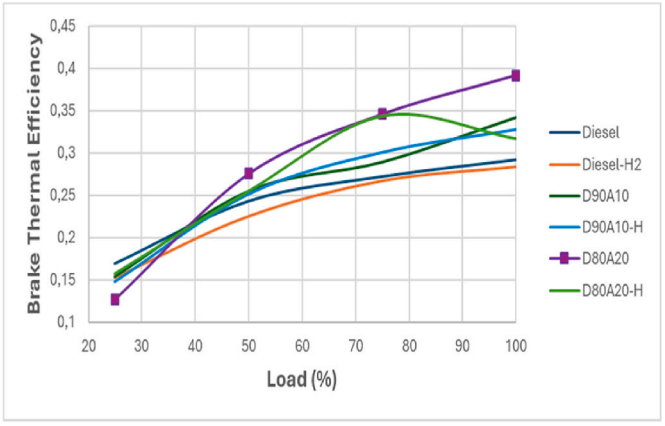


Fig. 3. Brake Thermal Efficiency (BTE).

cylinder pressures of different ammonia mixture ratios (0 %, 10 %, 20 %) combined with diesel fuel shows that an increase in the ammonia ratio leads to higher in cylinder pressure. The reason for the highest cylinder pressure being observed with the A20D80H10 fuel mixture is that the combined use of hydrogen and ammonia provides a more effective auto-ignition temperature compared to direct hydrogen use in diesel engines. While the high flame speed of hydrogen increases the peak pressure, the low flame speed of ammonia balances this pressure. This mixture helps optimize the peak cylinder pressure throughout the engine cycle [16]. Thirdly, if the lines representing mixtures with ammonium hydroxide ratios increased from 0 % to 20 % are examined, the peak cylinder pressure rises as the ammonium hydroxide ratio increases. This is related to the fact that combustion occurs a few CA before the top dead center (TDC) [8]. Fourthly, it is observed that adding hydrogen to the 20 % ammonium hydroxide mixture and to the 10 % ammonium hydroxide mixture requires a high proportion of ammonium hydroxide for effective hydrogen performance. Specifically, a higher ratio of ammonium hydroxide is necessary to increase in-cylinder pressure and prevent ignition delay.

3.2. Exhaust temperatures and emissions

3.2.1. Exhaust temperatures

Fig. 5 shows that an increase in the amount of ammonia significantly decreased the peak exhaust temperatures. This decrease was observed in parallel with the information obtained from previous studies that the high heat of vaporization of ammonia and lower flame temperature reduced the exhaust temperatures [19].

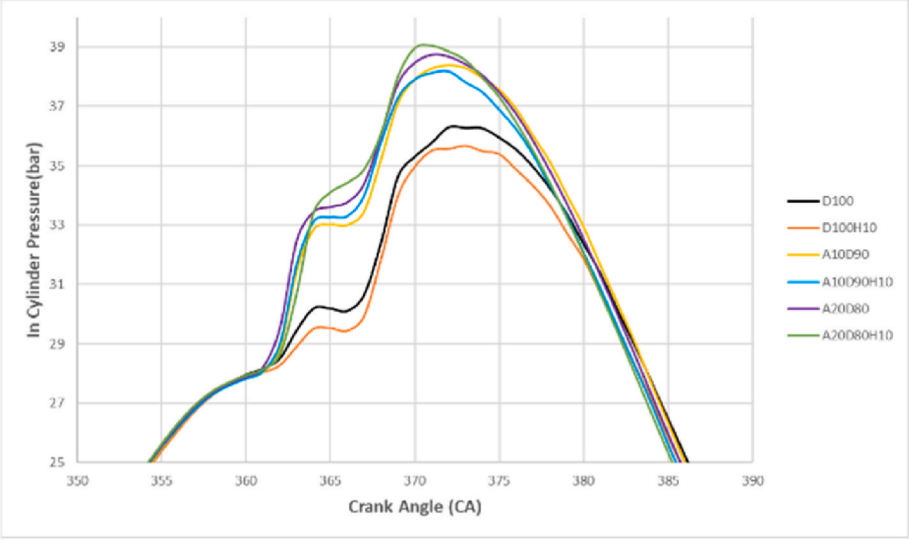


Fig. 4. In cylinder pressure under 300 Nm load.

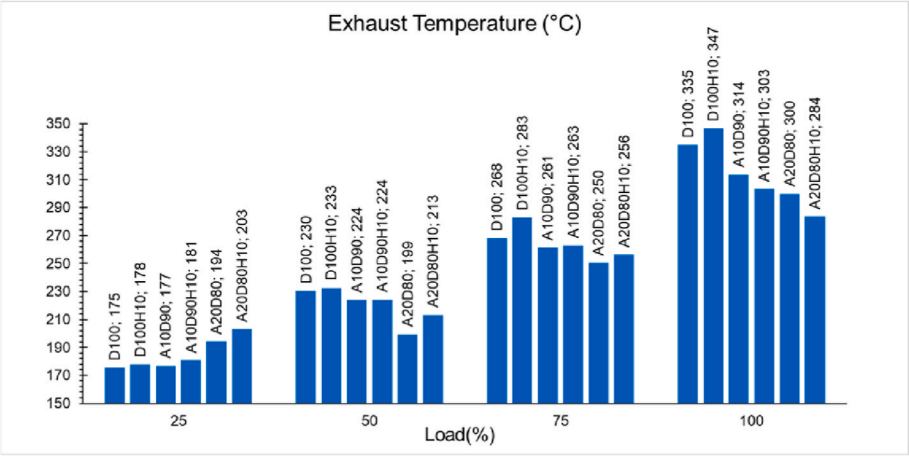


Fig. 5. Exhaust temperatures.

The combustion characteristics of ammonia and hydrogen show high exhaust temperatures due to the higher calorific value of hydrogen. The use of hydrogen has increased exhaust temperatures not only because of the higher LHV but also because it replaces the air used in the intake and generates higher flame temperatures compared to air [4,32]. The addition of ammonia stabilizes the exhaust temperatures due to the slower combustion process [8,20,21].

3.2.2. Exhaust emissions

3.2.2.1. Nitrogen Oxides emissions (NOx). According to the graph given in Fig. 6, as the amount of ammonium hydroxide in the fuel mixture increased, NO_x emissions increased at low loads. Conversely, at medium and full loads, increasing the amount of ammonium hydroxide decreased NO_x emissions. The presence of hydrogen in the mixture of hydrogen and diesel and in the mixture formed by adding hydrogen to the diesel fuel mixture with rich ammonium hydroxide reduced NO_x emissions at low and medium loads. At high loads (>90 %), the addition of hydrogen to a mixture with a low ammonia content will reduce NO_x levels. In experiments at low loads, thermal NO_x formation increases due to low in-cylinder temperatures. On the other hand, as the load amount increases, combustion efficiency and high in-cylinder temperatures cause a decrease in NO_x emissions. The addition of hydrogen gas will optimize the combustion process and reduce NO_x emissions [4–6,16]. On the other hand, it is specifically stated in the literature that the use of hydrogen in a diesel engine increases NO_x emissions [23]. However, this study shows that NO_x emissions will decrease with the effective use of ammonia and hydrogen (see Fig. 6).

3.2.2.2. Unburned hydrocarbon emissions (HC). In the fuel mixture formed by adding hydrogen to pure diesel fuel, HC emissions increased at all loads (see Fig. 7). However, lower HC emissions were obtained in fuels with higher ammonium hydroxide content. These results show that the addition of hydrogen increases HC emissions. The lowest HC level was observed in the mixture of ammonium hydroxide and diesel. In addition, HC emissions decreased as the ammonium hydroxide ratio increased. These results emphasize that HC emissions can be reduced by using ammonium hydroxide. Ammonium hydroxide (NH_4OH) produces water vapor in the combustion process, and thanks to this water vapor, it reduces the in-cylinder temperature and reduces the formation of unburned hydrocarbons by optimizing combustion reactions [11].

3.2.2.3. CO_2 emissions. According to the graph given in Fig. 8, CO_2 emissions decrease as the amount of ammonia increases at medium and high loads. Likewise, a decrease in CO_2 emissions was observed by adding hydrogen to diesel fuel. However, adding hydrogen to diesel and ammonia mixtures increases CO_2 emissions. This result complicates the effects of ammonia and hydrogen on CO_2 emissions when used together. Therefore, a careful balancing of emission control strategies is required when alternative fuels are to be used in diesel engines (see Fig. 8).

3.2.2.4. CO emissions. A decrease in CO emissions was observed at high loads. A10D90 fuel has the lowest CO emissions (see Fig. 9). As the ammonium hydroxide ratio increases, CO increases at low loads, but CO decreases at high loads. The fuel formed by adding hydrogen to pure diesel has reduced CO emissions at medium and high loads. However, CO emissions increased with the addition of hydrogen to fuel with high ammonium hydroxide content. These results indicate that the lowest CO emissions can be obtained by keeping the amount of ammonium hydroxide at an optimal level and using the engine at high loads. Low CO amounts at high loads are an indication of complete combustion [28]. As can be seen from the BTE graph, D80A20 fuel, which has high BTE, contains the lowest CO ratio. Bayramoğlu, K. emphasized the reduction in CO emissions when ammonia use is kept at an optimum level [6]. In his study, Nadimi et al. suggested that combustion would be better at high loads and CO emissions would decrease [8]. However, Jamrozik et al. stated that CO emissions increase even more at low engine loads [20]. Engine load and ammonium utilization management should be done well.

4. Conclusion

In this study, by adding H_2 gas through the intake manifold and blending a 25 % purity ammonium hydroxide solution (NH_4OH) with pure diesel in specific ratios, the effects of the prepared mixtures on in-cylinder pressure, engine performance, exhaust temperatures, and emissions were experimentally investigated in a 6-cylinder diesel engine. The results demonstrated that these mixtures provide significant benefits in both improving Brake Thermal Efficiency (BTE) and controlling emissions. However, it was revealed that the interactions between the mixtures are complex, and different effects may be observed in different engine types.

- The addition of ammonium hydroxide (NH_4OH) has meaningfully increased brake thermal efficiency at medium and full loads. The A20D80 mixture using 20 % NH_4OH by weight has achieved a 34.12 % increase in BTE compared to pure diesel. This is explained by the fact that NH_4OH optimizes the combustion process and reduces fuel consumption at high loads. Adding hydrogen at 10 % energy content

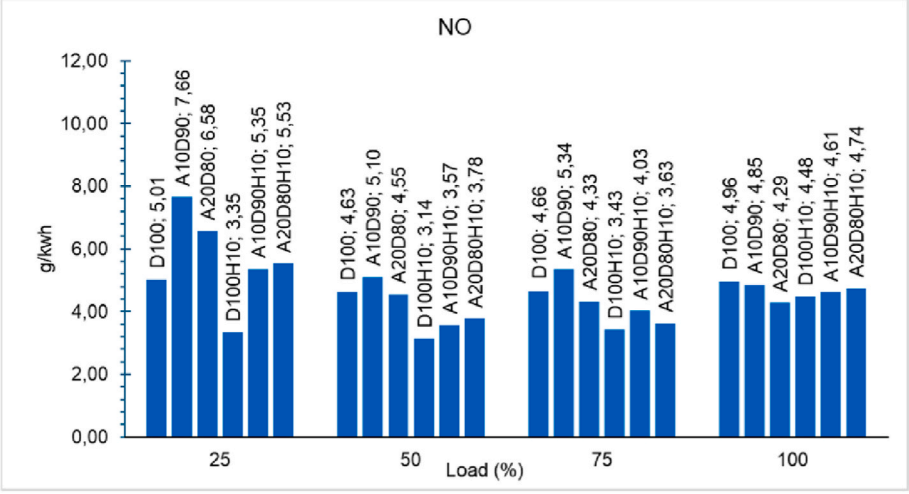


Fig. 6. NOx emissions.

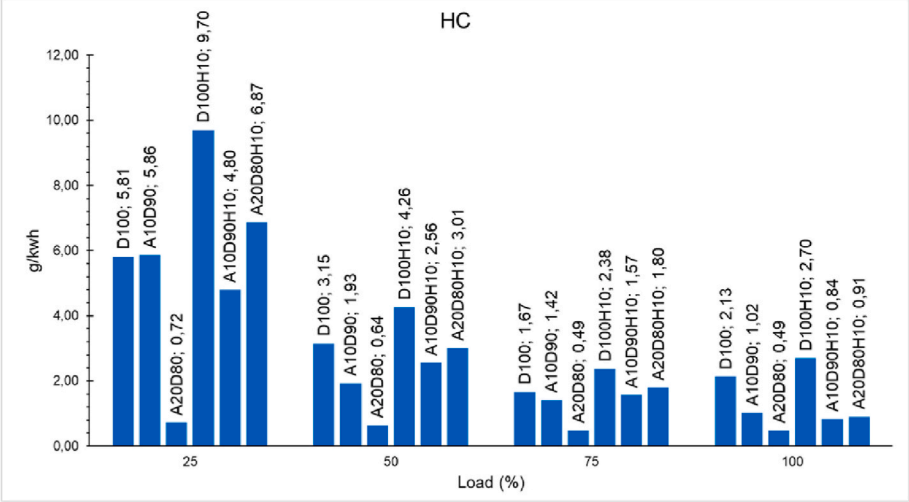


Fig. 7. HC emissions.

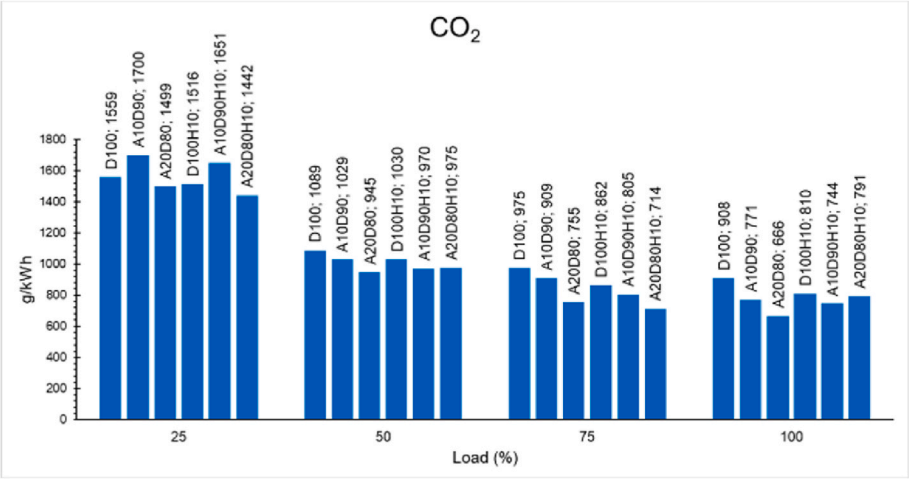


Fig. 8. CO_2 emissions.

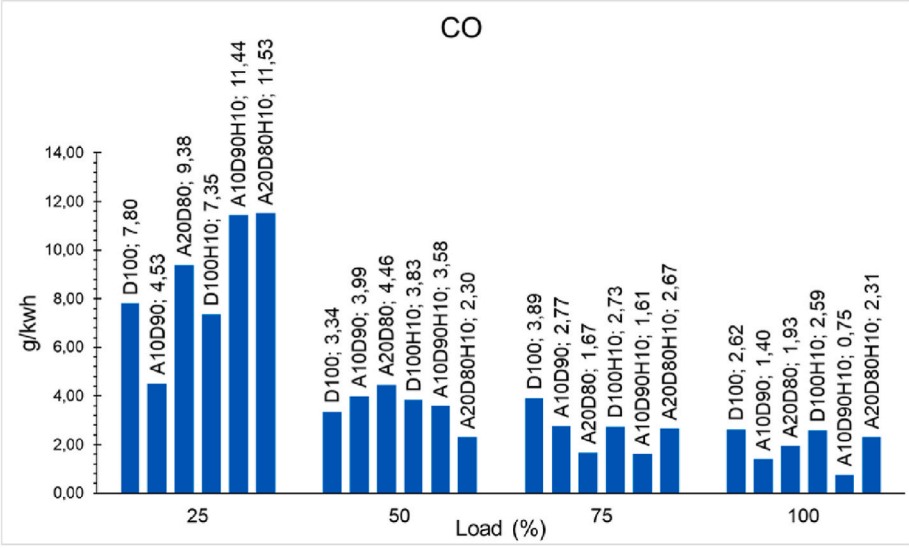


Fig. 9. CO emissions.

reduced ICP by 1.72 %, resulting in an ignition delay of approximately 1 crank angle. This was due to the high auto-ignition temperature of hydrogen, which causes ignition delay. As can be seen in the graph given in Fig. 3, the orange line (Diesel-H2) and the light blue line (D90A10-H) show a synergistic effect when ammonia and hydrogen are used together. It is about 6 % more efficient.

- Compared to pure diesel fuel, adding ammonium hydroxide to the blend decreased the peak temperatures. The exhaust temperature, which reached 335 °C degrees at full load in pure diesel, decreased to 295 °C degrees in the blend with a 10 wt% ammonium hydroxide additive. Exhaust temperatures decreased by approximately 11.94 %. and in contrast, adding percent hydrogen to pure diesel increased exhaust temperatures by approximately 4.48 %. However, adding ammonium hydroxide and hydrogen fuels to diesel stabilized the exhaust peak temperatures. The addition of both fuels (ammonia/hydrogen) to pure diesel reduced the temperature from 335 °C degrees to 285 °C degrees, a reduction of about 14.93 %. This is explained by the slower combustion of ammonia in ammonium hydroxide and the faster combustion of hydrogen.
- When the fuels were analyzed in terms of emissions, the presence of ammonium hydroxide and hydrogen varied according to different loads and usage amounts. Especially at high loads, the use of ammonium hydroxide reduced CO_2 and HC emissions, while the addition of hydrogen at low and medium loads reduced NO_x emissions. However, the addition of hydrogen to mixtures containing ammonium hydroxide at high loads increased CO_2 emissions. With these results, it was found that the fuels used in the blends should be carefully balanced.

In future studies, the results of the use of the fuels used in this study at different engine loads and in different amounts should be examined in more detail, and it should be observed how the engine and other support systems required for the operation of the engine system will be affected in the long term. In addition, the industrial applicability, lifetime, and cost-effectiveness of these mixtures should be evaluated. These studies can make significant contributions both to the literature and to the search for sustainable, environmentally friendly, clean energy.

CRediT authorship contribution statement

Mehmet Sarıtaş: Writing – review & editing, Writing – original draft, Project administration. **Volkan Sabri Kül:** Writing – review & editing, Writing – original draft, Project administration. **Selahaddin Orhan Akansu:** Writing – review & editing, Writing – original draft, Supervision, Project administration. **Happy Sinkala:** 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.*One of our authors Prof. Dr. Selahaddin Orhan Akansu is also the guest editor for the special issue of your journal.

Acknowledgement

In this study, the authors used the equipment purchased from Erciyes University Engines Laboratory with the support of "Erciyes University **Scientific Research Projects Coordination Office (BAP)**". They would like to thank them for their support.

References

[1] Ritchie H, Roser M. Fossil fuels. Our World in Data; 2018. https://ourworldindata.org/fossil-fuels [Accesses date:02.03.2025].
[2] Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M. Global temperature change. Proc Natl Acad Sci 2006;103(39):14288–93. https://doi.org/10.1073/pnas.0606291103.
[3] Shadidi B, Najafi G, Yusaf T. A review of hydrogen as a fuel in internal combustion engines. Energies 2021;14:6209. https://doi.org/10.3390/en14196209.
[4] Wang B, Yang C, Wang H, Hu D, Wang Y. Effect of Diesel-Ignited Ammonia/Hydrogen mixture fuel combustion on engine combustion and emission performance. Fuel 2023;331:125865. https://doi.org/10.1016/j.fuel.2022.125865.
[5] Qian Y, Pei X, Zheng L, Mi S, Ju D, Zhou D, Lu X. Improving thermal efficiency of an ammonia-diesel dual-fuel compression ignition engine with the addition of premixed low-proportion hydrogen. Int J Hydrogen Energy 2024;58:707–16. https://doi.org/10.1016/j.ijhydene.2024.01.235.
[6] Bayramoğlu K. Energy and exergy analysis of diesel-hydrogen and diesel-ammonia fuel blends in diesel engine. J ETA Marit Sci 2024;12(2). https://doi.org/10.4274/jems.2024.46503.
[7] Koten H. Hydrogen effects on the diesel engine performance and emissions. Int J Hydrogen Energy 2018;43(22):10511–9. https://doi.org/10.1016/j.ijhydene.2018.04.146.
[8] Nadimi E, Przybyła G, Lewandowski MT, Adamczyk W. Effects of ammonia on combustion, emissions, and performance of the ammonia/diesel dual-fuel compression ignition engine. J Energy Inst 2023;107:101158. https://doi.org/10.1016/j.joei.2022.101158.
[9] Hong C, Ji C, Wang S, Xin G, Wang Z, Meng H, Yang J. An experimental study of various load control strategies for an ammonia/hydrogen dual-fuel engine with the Miller cycle. Fuel Process Technol 2023;247:107780. https://doi.org/10.1016/j.fuproc.2023.107780.
[10] Kül VS, Akansu SO. The investigation of the performance and exhaust emissions of the compression-ignition engine with a mixture of diesel and aluminum particles. Process Saf Environ Prot 2024;189:1161–72. https://doi.org/10.1016/j.psep.2024.07.003.
[11] Kül VS, Akansu SO, Çınar G. Experimental investigation of the effects of aqueous ammonia and water mixtures on the efficiency and emissions of a compression ignition engine. Process Saf Environ Prot 2024;191:1495–503. https://doi.org/10.1016/j.psep.2024.09.051.
[12] Qi Y, Liu W, Liu S, Wang W, Peng Y, Wang Z. A review on ammonia-hydrogen fueled internal combustion engines. ETransportation 2023;18:100288. https://doi.org/10.1016/j.etran.2023.100288.
[13] Tsujimura T, Suzuki Y. The utilization of hydrogen in hydrogen/diesel dual fuel engine. Int J Hydrogen Energy 2017;42(19):14019–29. https://doi.org/10.1016/j.ijhydene.2017.01.152.
[14] Wang B, Wang H, Duan B, Yang C, Hu D, Wang Y. Effect of ammonia/hydrogen mixture ratio on engine combustion and emission performance at different inlet temperatures. Energy 2023;272:127110. https://doi.org/10.1016/j.energy.2023.127110.
[15] Dhas AAG, Almoallim HS, Ganeshan S, Anbarasu A, Beata G. In-depth study of waste cooking oil blends with hydrogen and ammonia in internal combustion engine: performance and emission study. Fuel 2024;369:131663. https://doi.org/10.1016/j.fuel.2024.131663.
[16] Anderson A, Athimoolam A, Chinnathambi A, Gunasekar P, Ramesh PT. Fuel 2024;369:131753. https://doi.org/10.1016/j.fuel.2024.131753.
[17] Coskun AD, Kul VS, Akansu SO. Experimental investigation of the effect of acetone additive to diesel fuel on engine performance and exhaust emissions at partial loads. Energy Environ Storage 2023;3(1):12–8. https://doi.org/10.52924/WQJR9374.
[18] Hosseini SH, Tsolakis A, Alagumalai A, Mahian O, Lam SS, Pan J, Aghbashlo M. Use of hydrogen in dual-fuel diesel engines. Prog Energy Combust Sci 2023;98:10110. https://doi.org/10.1016/j.pecs.2023.101100.
[19] Li J, Lai S, Chen D, Wu R, Kobayashi N, Deng L, Huang H. A review on combustion characteristics of ammonia as a carbon-free fuel. Front Energy Res 2021;9:760356. https://doi.org/10.3389/fenrg.2021.760356.
[20] Jamrozik A, Tutak W, Pyrc M, Gruca M, Kočiško M. Study on co-combustion of diesel fuel with oxygenated alcohols in a compression ignition dual-fuel engine. Fuel 2018;221:329–45. https://doi.org/10.1016/j.fuel.2018.02.098.
[21] Gnanamoorthi V, Vimalananth VT. Effect of hydrogen fuel at higher flow rate under dual fuel mode in CRDI diesel engine. Int J Hydrogen Energy 2020;45(33):16874–89. https://doi.org/10.1016/j.ijhydene.2020.04.145.
[22] Zhang Z, Hu J, Yang D, Yin Z, Lu K, Tan D. A comprehensive assessment over the environmental impact and combustion efficiency of using ammonia/hydrogen/diesel blends in a diesel engine. Energy 2024;303:131955. https://doi.org/10.1016/j.energy.2024.131955.
[23] Jamrozik A, Tutak W. The impact of ammonia and hydrogen additives on the combustion characteristics, performance, stability and emissions of an industrial DF diesel engine. Appl Therm Eng 2024;257:124189. https://doi.org/10.1016/j.applthermaleng.2024.124189.
[24] Ramalingam K, Kandasamy M, Subbiah G, Vellaiyan S, Devarajan Y, Chandran D, Raviadaran R. Energy, environmental, and economic benefits of hydrogen-enriched biofuel using ammonium hydroxide in reactivity-controlled compression ignition engines. Results Eng 2024;24:103672. https://doi.org/10.1016/j.rineng.2024.103672.
[25] Fakhari AH, Gharehghani A, Salahi MM, Andwari AM. RCCI combustion of ammonia in dual fuel engine with early injection of diesel fuel. Fuel 2024;365:131182. https://doi.org/10.1016/j.fuel.2024.131182.
[26] Vellaiyan S. Transforming wastewater-derived algae biodiesel with ammonium hydroxide emulsion for enhanced energy efficiency and emission reduction. Results Eng 2024;24:103332. https://doi.org/10.1016/j.rineng.2024.103332.

[27] Subramani AK, Duraisamy G, Govindan N, Hossain AK. An innovative method of ammonia use in a light-duty automotive diesel engine to enhance diesel combustion, performance, and emissions. Int J Hydrogen Energy 2024;49:38–58. https://doi.org/10.1016/j.ijhydene.2023.06.183.
[28] Kül VS, Sarıtaş M. Investigation of the effect of stearic acid addition to diesel on combustion in a compression ignition engine, energy. Environ Storage 2025;05–01: 20–4. https://doi.org/10.52924/ZDOJ8219.
[29] Kül VS, Akansu SO, Sarıtaş M, Sinkala H, Ünalan S. Investigation of the effect of utilisation of nano boron, diesel and biodiesel fuels with together hydrogen in a compression ignition engine on combustion characteristics. Int J Thermofluids 2025:101232. https://doi.org/10.1016/j.ijft.2025.101232.
[30] Silva IP, Lima RM, Silva GF, Ruzene DS, Silva DP. Thermodynamic equilibrium model based on stoichiometric method for biomass gasification: a review of model modifications. Renew Sustain Energy Rev 2019;114:109305. https://doi.org/10.1016/j.rser.2019.109305.
[31] Frost J, Tall A, Sheriff AM, Schönborn A, Hellier P. An experimental and modelling study of dual fuel aqueous ammonia and diesel combustion in a single cylinder compression ignition engine. Int J Hydrogen Energy 2021;46(71):35495–510. https://doi.org/10.1016/j.ijhydene.2021.08.089.
[32] Duraisamy B, Varuvel EG, Palanichamy S, Subramanian B, Stanley MJ, Madheswaran DK. Impact of hydrogen addition on diesel engine performance, emissions, combustion, and vibration characteristics using a Prosopis Juliflora methyl ester-decanol blend as pilot fuel. Int J Hydrogen Energy 2024;75:12–23. https://doi.org/10.1016/j.ijhydene.2023.12.047.
[33] Al-Dawody MF, Al-Obaidi W, Aboud ED, Abdulwahid MA, Al-Farhany K, Jamshed W, Iqbal A. Mechanical engineering advantages of a dual fuel diesel engine powered by diesel and aqueous ammonia blends. Fuel 2023;346:128398. https://doi.org/10.1016/j.fuel.2023.128398.