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Preliminary research on the co-combustion process of ammonia in a compression-ignition engine

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In the face of increasing requirements for exhaust emission reduction and the search for alternative fuels, ammonia is being considered as a potential fuel component in compression-ignition engines. The aim of this study was to conduct preliminary research on the co-combustion process of ammonia with diesel fuel and to assess its impact on exhaust emissions and engine performance characteristics. In the first stage, measurements of ammonia concentration in the exhaust gases were carried out to determine its presence in the exhaust stream. Next, optimal engine operating points were determined for various fuel ratios, enabling a comparative analysis of the combustion of pure diesel fuel and its mixtures with ammonia. In the final phase, key exhaust emission components were measured. The results indicate both potential benefits and challenges associated with using ammonia as a fuel additive in diesel engines. The conducted research provides a basis for further analysis aimed at optimizing the ammonia co-combustion process to improve efficiency and reduce its environmental impact.

Key words: *ammonia combustion, combustion engines, combustion efficiency, alternative fuels, diesel engine decarbonization*

1. Introduction

Rising environmental protection requirements, reductions in greenhouse gas emissions and the need to decouple the transport sector from fossil fuels have intensified the search for alternative energy carriers. This is particularly relevant for compression-ignition (CI) engines, which dominate in heavy transport, agriculture and distributed power generation, creating a demand for low-emission fuels that can be used with minimal modifications to existing technologies. In this context, ammonia (NH_3) is gaining attention as a potential fuel component or even as a standalone fuel [20].

Ammonia is a chemical compound with physical and chemical properties that has been used for decades in the chemical and fertilizer industries. Its main advantages as a fuel includes: zero CO_2 emissions during combustion, the ability to store and transport it in liquid form, a well-developed distribution infrastructure and a high hydrogen content (17.6% by weight). Unlike pure hydrogen, which requires very high-pressure or low-temperature tanks, ammonia can be stored as a liquid at relatively low pressures (about 10 bar at ambient temperature), making it much more practical as an energy carrier. However, despite its advantages, using ammonia as a fuel in combustion engines involves significant limitations. Its lower heating value (18.6 MJ/kg) is more than twice as low as that of diesel fuel (about 42–45 MJ/kg), which means more mass needs to be burned to obtain the same amount of energy. Additionally, ammonia's auto-ignition temperature (~651°C) is significantly higher than that of typical CI engine fuels (about 210°C for diesel), making pure ammonia less reactive and harder to ignite under standard engine conditions [3, 11, 13, 17].

Because of these issues, co-combustion of ammonia with a conventional fuel like diesel is increasingly proposed. This hybrid approach leverages the advantages of both fuels: the high reactivity and energy density of diesel and the carbon-free combustion of ammonia. In compression ignition (CI) engines, diesel injection can act as an ignition source for the ammonia-air mixture, promoting oxidation and improving combustion stability. By partially replacing diesel with ammonia, the overall reliance on fossil fuels can be reduced with implications for both efficiency and emissions [7, 13].

Another challenge in using ammonia effectively as an engine fuel is its low laminar flame speed, around 0.07 m/s, compared to methane or propane (0.3–0.4 m/s) and hydrogen (over 2 m/s). This low flame speed results in slower combustion of the fuel-air mixture, potentially leading to combustion irregularities, longer cycle durations and increased emissions of unburned ammonia. It is especially problematic in CI engine cyclic operation, where fast and stable combustion is essential. Therefore, research into ignition support and flame propagation acceleration strategies – such as pilot fuel injection, hydrogen blending or combustion chamber geometry modification is increasingly important [1, 19, 4, 21].

Ammonia combustion involves a complex reaction kinetics. The main combustion reaction is:

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O \quad (1)$$

However, under practical engine conditions, with temperature gradients, uneven mixing and the presence of soot or unburned hydrocarbons – side reactions can occur, forming nitrogen oxides (NO, NO_2) and leading to unburned ammonia emissions ("NH_3 slip"). This is especially concerning due to ammonia's toxicity and pungent odor, which are noticeable even at a few ppm.

Thus, key challenges in ammonia-diesel co-combustion include selecting appropriate fuel ratios, engine operating conditions and fuel delivery techniques to optimally use the energy properties of the mixture while minimizing unwanted exhaust components. Additionally, the effects on overall efficiency – such as ignition delay, combustion duration, peak cylinder pressure and pressure-volume curve characteristics must be considered [10, 13, 16].

An increasing number of experimental and numerical studies on ammonia combustion have been published, including fuel cells, gas burners and piston engines. These studies show that even small additions of high-reactivity fuel (e.g., diesel or hydrogen) can improve ammonia combustion and reduce unreacted molecule emissions. Still, many questions remain, especially regarding NO_x emissions under various operating conditions, flame stability and long-term engine component durability.

Ammonia (NH_3) is increasingly considered in the literature as a low-carbon energy carrier with potential use in fuel cells and combustion engines. Unlike hydrogen, ammonia is easier to store as a liquid and benefits from existing infrastructure. According to Zamfirescu and Dincer [22] producing "green ammonia" from renewable energy, can eliminate CO_2 emissions across its lifecycle.

Combustion studies highlight ammonia's low reactivity, causing ignition issues and slow flame propagation. A laminar flame speed of ~0.07 m/s [6] is significantly lower than that of typical hydrocarbon fuels (0.3–0.4 m/s for methane, > 2 m/s for hydrogen), presenting a key technological challenge.

Studies have shown that even with ammonia shares of 10–30% by volume, stable engine operation is possible when diesel is used as a pilot fuel. Zhang et al. [23] reported reduced CO and HC emissions, while Reiter and Kong [14] confirmed improved ignition and combustion stability.

Lee et al. [8] pointed out a significant increase in NO_x emissions with higher ammonia content. This stems from Zeldovich reaction mechanisms and the presence of excess unburned ammonia ("NH_3 slip"). These researchers recommend EGR systems and selective catalytic reduction (SCR) for emission control.

Ammonia combustion is governed by complex free radical kinetics involving H, OH and O radicals. Mørch et al. [12] noted that proper combustion conditions, moderate excess air and controlled peak temperatures can reduce NO_x emissions. They also highlighted that the pilot fuel injection strategy and timing significantly affect combustion efficiency. CFD models (e.g., using CHEMKIN) are increasingly applied to predict emissions for various combustion chamber setups.

Ammonia-fueled engine prototypes are being developed for road and marine transport. Toyota and Hyundai [20] are working on demonstration projects involving co-combustion of ammonia with diesel or hydrogen in commercial vehicle engines. MAN Energy Solutions is testing ammonia in medium-speed marine engines [9]. These projects focus on:

– exhaust gas recirculation (EGR) rates
– material resistance to ammonia (corrosion and degradation)
– NH_3 slip detection and mitigation.

Existing studies clearly show that pure ammonia combustion in CI engines is highly problematic. High ignition temperature, low reactivity, and slow flame speed make the use of pure ammonia technologically challenging. Co-combustion with a pilot fuel like diesel offers a promising workaround for ignition and combustion stability issues. Key factors for successful implementation include proper fuel ratio, injection timing, and combustion chamber thermal conditions. Despite growing research, experimental data on full-scale CI engines operating under realistic conditions remains limited [5, 15, 18].

The present study aims to analyze the co-combustion of ammonia with diesel in a CI engine, focusing on:

– ammonia combustion efficiency (including detection of residuals in exhaust gases)
– the impact of fuel mixture composition on key engine parameters.

Additionally, the study examines how co-combustion affects exhaust smoke, an indirect indicator of particulate matter from incomplete combustion. The experiment was conducted using an engine test bench under partial load and constant engine speed. The analysis in this preliminary study included combustion/overall efficiency derived from fuel flow, brake power and exhaust smoke. Gaseous emissions (NO_x, NH_3, CO) and particle number (PN) were not part of the measurement scope.

2. Methodology

The tests were conducted on an engine test bench (Fig. 1) equipped with a Fiat 1.3 JTD compression-ignition engine with a nominal power output of 51 kW, a Schenck W150 eddy-current dynamometer and a data acquisition system for recording key engine operating parameters, including torque [Nm], engine speed [rpm], fuel consumption [g/h], exhaust gas temperature [°C], intake air temperature, pressure and exhaust opacity (FSN). Diesel fuel consumption was measured gravimetrically using an Automex fuel balance with an accuracy of ±0.1 g. The fuel mass flow rate was recorded in grams per hour (g/h), enabling precise calculation of specific fuel consumption and overall combustion. Ammonia was supplied to the engine in gaseous form via a custom-designed mixing system integrated into the intake manifold downstream of the charge air cooler. The ammonia source was a high-pressure cylinder (61 L) from Messer, containing Ammonia 3.8 (99.98%) and corresponding to 32 kg of gas. The operating pressure of the cylinder was 8–10 bar at room temperature (20°C), and the valve used was compliant with DIN standards for toxic gases. Ammonia was delivered in the gas phase, and its temperature was maintained within the range of 15–25°C to ensure repeatability of the mixing process.

The measurement of the ammonia flow rate was carried out using a rotameter EK2/NR, with simultaneous monitoring of the gas temperature. To ensure operational safety, the guidelines provided by the gas manufacturer, as well as occupational health and safety regulations related to the use of toxic substances, were strictly followed.

The load characteristics were determined at a constant engine speed of 1200 rpm and within a load range of 20 to 80 Nm. After achieving thermal stabilization of the engine at a given operating point, its performance parameters were recorded while fueled exclusively with diesel. Subsequently, ammonia was introduced into the intake system and data on the consumption of both fuels as well as exhaust smoke opacity (FSN values, converted to mg/m³) were collected. Other gaseous pollutants (NO_x, NH_3, CO, PN) were not measured at this stage and will be addressed in follow-up studies.

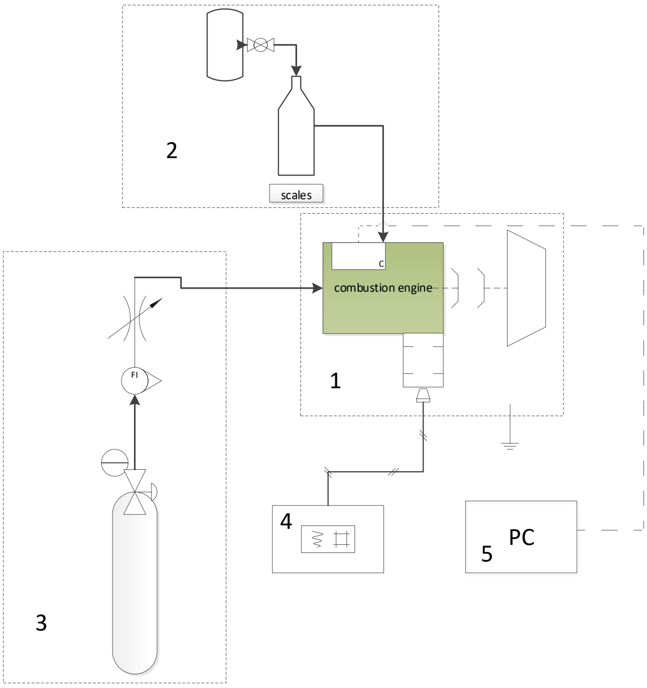

Fig. 1. Test bench schematic: 1) engine test bench, 2) fuel consumption measurement system (mass-based), 3) ammonia supply system, 4) AVL 415 smoke meter, 5) data acquisition computer

This operating point was chosen as a representative condition for low-to-medium speed operation, typical of stationary CI engines (e.g., generators, agricultural machinery). The fixed speed also ensured safe and stable conditions during preliminary trials with ammonia, enabling repeatable measurements. The selected load range corresponds to partial load operation, where efficiency and emission trade-offs are particularly relevant for practical applications.

In each case, exhaust gas opacity was measured using an AVL 415 smoke meter, which enabled the assessment of particulate matter content depending on the composition of the fuel mixture. A computer-based data acquisition system was used for data collection and recording, allowing real-time monitoring of engine performance parameters and measurement results.

Fig. 2. Test bench

The formula used to calculate the overall efficiency is as follows:

$$\eta_{comb} = \frac{P_{engine}}{\dot{m}_{NH3} * LHV_{NH3} + \dot{m}_{diesel} * LHV_{diesel}} \quad (2)$$

where: η – overall efficiency, P_{engine} – engine output power (mechanical), $\dot{m}_{nh3}$, ṁ_diesel – mass flow rates of ammonia and diesel fuel [kg/s], LHV – lower heating value of the respective fuel [MJ/kg].

The conversion of Filter Smoke Number (FSN) values obtained using the AVL 415 smoke meter into units of mg/m³ was based on an empirical relationship found in the literature:

$$PM = 1.63 \cdot e^{(1.08 \cdot FSN)} \quad (3)$$

where: PM – mass concentration of particulate matter in the exhaust gas [mg/m³], FSN – Filter Smoke Number measured directly by the smoke meter, e – base of the natural logarithm (≈ 2.718).

This formula [2] is based on standard measurement conditions for diesel engines fueled with conventional diesel. It should be noted that this conversion is approximate and does not substitute for direct gravimetric determination of particulate mass.

3. Results and experimental analysis

3.1. Influence of ammonia energy share in the fuel mixture on overall efficiency

The data were obtained based on actual efficiency measurements for individual fuel blends containing from 0 up to nearly 60% of ammonia energy share.

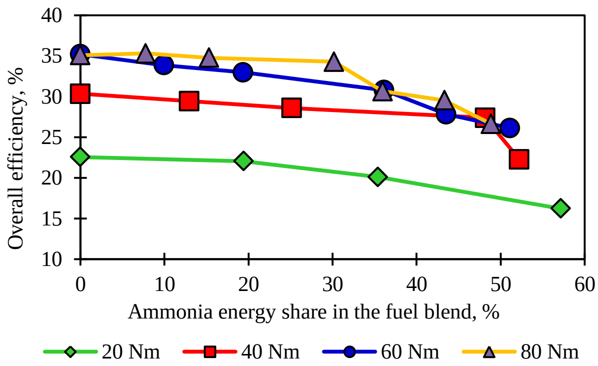

Fig. 3. Influence of the ammonia-derived energy share on overall efficiency at a constant engine speed of 1200 rpm under varying loads

For all analyzed cases, a consistent decrease in overall efficiency was observed as the percentage of ammonia energy in the fuel mixture increased. The highest efficiencies were obtained during combustion of pure diesel fuel. At the same time, the lowest were recorded for mixtures with the maximum ammonia content. Initial overall combustions (at 0% NH_3) were as follows:

1. 22.57% – 20 Nm
2. 30.33% – 40 Nm
3. 35.20% – 60 Nm
4. 35.08% – 80 Nm.

At the highest ammonia shares, the efficiencies decreased to:

1. 16.24% – 57.16% NH_3, 20 Nm
2. 22.27% – 52.21% NH_3, 40 Nm
3. 26.13% – 51.09% NH_3, 60 Nm
4. 26.64% – 48.85% NH_3, 80 Nm.

A detailed analysis of the measured parameters highlights how increasing ammonia content influences the combustion process under various load conditions. The decrease in overall efficiency with increasing ammonia energy share is clear and progresses non-linearly – most significant changes occur above ~30% NH_3. At low and medium loads (20–60 Nm), the largest absolute drops in efficiency were observed – up to 6–9 percentage points, corresponding to a relative decrease of approximately 25–30%. At the highest load (80 Nm), the efficiency drop was slightly less pronounced (from 35.08% to 26.64%) but still significant. The higher combustion chamber temperature at high load likely promotes better ammonia oxidation. The decrease in efficiency results directly from the properties of ammonia as a fuel: high ignition temperature, low lower heating value and limited reactivity under compression ignition conditions. Increasing amounts of unburned ammonia in the exhaust gases contribute to real energy losses. Despite these losses, the presence of unburned ammonia in the exhaust can be beneficial from the perspective of SCR (Selective Catalytic Reduction) systems, where ammonia acts as a reducing agent for NO_x. This opens the possibility of reducing or eliminating the need for AdBlue dosing. An integrated approach to combustion and exhaust aftertreatment may enable the implementation of ammonia-diesel co-combustion technology while maintaining acceptable efficiency and emission performance.

3.2. Influence of ammonia energy share in the fuel mixture of exhaust smoke opacity

Figure 4 presents the converted exhaust smoke opacity values expressed in mass units (mg/m³), calculated based on the FSN (Filter Smoke Number) measurement results. These values provide a more direct indication of the mass emission of particulate matter, which may be relevant from an environmental regulatory perspective. The data are detailed in Table 1.

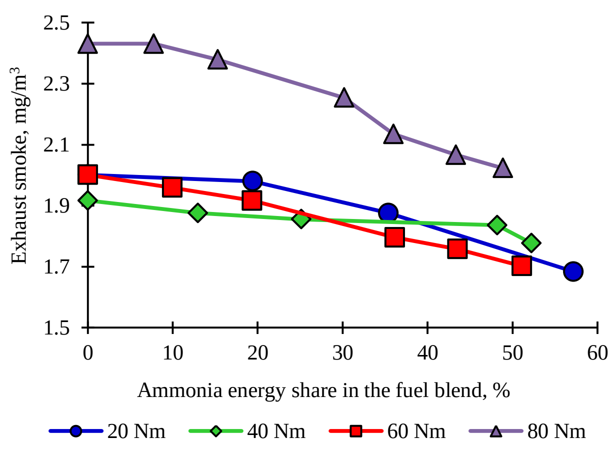

Fig. 4. Relationship between the ammonia-derived energy share (in dual-fuel operation: diesel injection + gaseous ammonia supply) and exhaust smoke opacity at 1200 rpm across different engine loads

Table 1. Effect of ammonia-derived energy share (dual-fuel mode: diesel + ammonia) on exhaust smoke (FSN and mg/m³) at different torque levels [Nm]

Nm	20						
%	0.00	19.41	35.39	57.16			
FSN	0.19	0.18	0.13	0.03			
mg/m³	2.00	1,98	1.88	1,68			
Nm	40						
%	0.00	12.94	25.13	48,.8	52.21		
FSN	0.15	0.13	0.12	0.11	0.08		
mg/m³	1.92	1.88	1.86	1.84	1.78		
Nm	60						
%	0.00	9.93	19.34	36.12	43.53	51.09	
FSN	0,.9	0.17	0.15	0.09	0.07	0.04	
mg/m³	2.00	1.96	1.92	1.80	1.76	1.70	
Nm	80						
%	0.00	7.77	15.30	30.16	35.97	43.31	48.85
FSN	0.37	0.37	0.35	0.30	0.25	0.22	0.20
mg/m³	2.43	2.43	2.38	2.25	2.14	2.07	2.02

The analysis below outlines the experimental findings regarding particulate emissions during ammonia-diesel co-combustion across different engine load conditions. At all load levels, a clear trend of decreasing particulate emissions (mg/m³) is observed with increasing ammonia-derived energy share in the fuel mixture. The highest absolute particulate emission values were recorded at the highest load (80 Nm), where emissions decreased from approximately 2.45 mg/m³ to 2.10 mg/m³ (a ~14% reduction). At lower loads (20–60 Nm), the relative reduction in particulate emissions was more pronounced, exceeding 15% at 20 Nm (from ~2.00 mg/m³ to ~1.65 mg/m³). Converting FSN to mg/m³ enables more accurate comparisons with emission standards. It confirms that ammonia co-combustion can positively impact the reduction of particulate mass emissions.

The following observations provide additional insight into the underlying causes and broader implications of the observed emission trends. The reduction in particulate matter with a higher ammonia energy share may be attributed to the lower carbon content in the blended fuel (hydrocarbons, ammonia), resulting in less soot formation during combustion. The presented results confirm a general trend: despite a decrease in thermal efficiency, ammonia-containing mixtures exhibit a more favorable particulate emission profile, which may be important in the context of air quality regulations and decarbonization strategies.

Reference of results to current emission standards

To enhance the practical relevance of the obtained results, the converted filter smoke number (FSN) values expressed in mass units (mg/m³) were compared with the current emission standards in force within the European Union. Although the conducted study was experimental in nature and did not follow a full homologation cycle (e.g., WLTP or NRTC), The measured particulate matter emissions can be approximately compared with regulatory thresholds applicable to various engine categories. Examples of particulate matter emission standards:

1. Euro 6d (for diesel passenger vehicles):
   – particulate mass: 4.5 mg/km
   – particle number: 6 × 10^{11}/km.
2. Stage V (for non-road mobile machinery and stationary engines):
   – for power range 19–56 kW: 15 mg/m³ (or 0.015 g/kWh)
   – for higher power ranges (e.g., 56–130 kW): limits are similar or slightly higher.

In the conducted tests, the highest measured particulate emission value (at 80 Nm torque and 0% ammonia) was approximately 2.45 mg/m³. In contrast, the lowest value for the same operating point (with 48.85% ammonia) dropped to 2.10 mg/m³. At lower loads, emissions decreased even further, reaching 1.65 mg/m³ at 20 Nm and ~57% ammonia. This indicates that all measured particulate values are significantly below the 15 mg/m³ limit defined in the Stage V standard, regardless of the ammonia energy share. Ammonia co-combustion contributes to a 10–20% reduction in particulate emissions, further distancing the results from the regulatory thresholds. Even under suboptimal conditions (highest load, low ammonia content) the powertrain remains compliant with emission standards applicable to modern non-road engines.

From an environmental regulatory perspective, the results clearly demonstrate that co-combustion of ammonia with diesel fuel can be implemented without the risk of exceeding permissible particulate matter (PM) emission limits, even at high ammonia energy shares in the fuel mixture. The measured PM emission levels remain fully compliant with Stage V standards, indicating the potential applicability of this solution in engines used in construction machinery, power generators, and off-road equipment. The reduction in PM mass emissions observed during ammonia co-combustion may be considered a significant environmental benefit of this technology, not only in terms of reducing local soot emissions but also in contributing to the mitigation of low-stack emissions and the improvement of air quality. However, it is important to note that the current data only reflect particulate emissions. The comparison to EU regulatory PM limits is illustrative. The study did not follow a certification cycle nor did it measure PN/NO_x/NH_3/CO. The lack of measurements for gaseous pollutants highlights the need for further studies before this combustion concept can be fully classified as compliant with Euro or Stage V emission regulations.

3.3. Decrease in co-combustion efficiency depending on the ammonia-derived energy share in the fuel mixture

The analysis considered the decrease in overall efficiency of a compression-ignition engine as a function of the increasing ammonia-derived energy share in the fuel mixture, across four engine load levels: 20, 40, 60 and 80 Nm (all at a constant speed of 1200 rpm). As a reference point, the efficiency values obtained with diesel-only fueling were adopted, amounting to:

– 22.57% at 1200 rpm, 20 Nm
– 30.33% at 1200 rpm, 40 Nm
– 35.20% at 1200 rpm, 60 Nm
– 35.08% at 1200 rpm, 80 Nm.

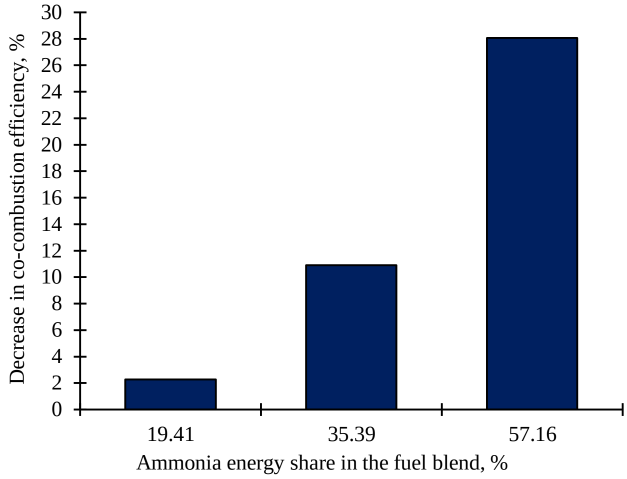

Fig. 5. Decrease in co-combustion efficiency depending on the ammonia energy share in the fuel blend at an engine speed of 1200 rpm and a load of 20 Nm

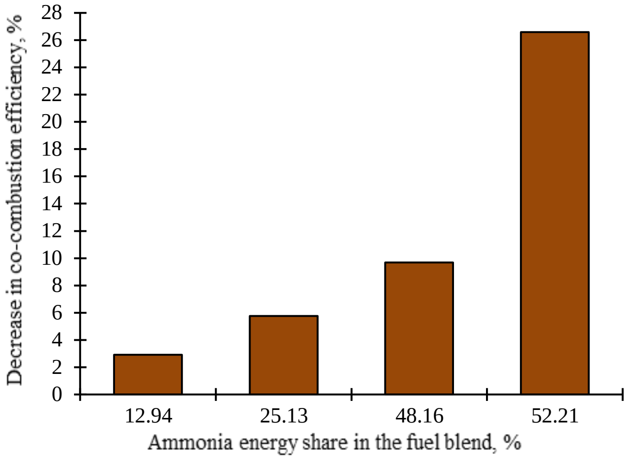

Fig. 6. Decrease in co-combustion efficiency depending on the ammonia energy share in the fuel blend at an engine speed of 1200 rpm and a load of 40 Nm

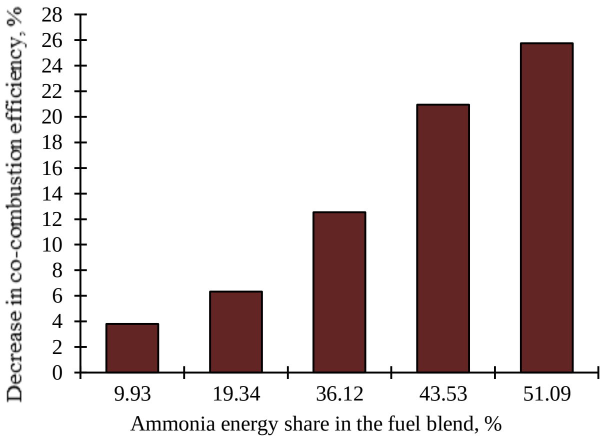

Fig. 7. Decrease in co-combustion efficiency depending on the ammonia energy share in the fuel blend at an engine speed of 1200 rpm and a load of 60 Nm

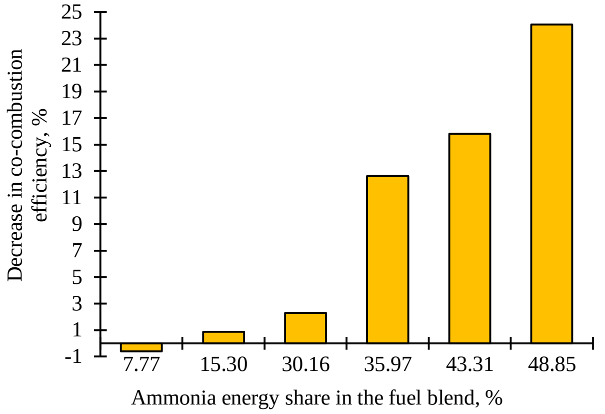

Fig. 8. Decrease in co-combustion efficiency depending on the ammonia energy share in the fuel blend at an engine speed of 1200 rpm and a load of 80 Nm

As the ammonia-derived energy share in the fuel mixture increased, a consistent decline in overall efficiency was observed. These changes are illustrated in Fig. 5–8 as a percentage drop in efficiency relative to the baseline diesel-only values.

The analysis below highlights how increasing the ammonia-derived energy share in a diesel–ammonia fuel blend affects overall efficiency under varying load conditions. It also outlines key patterns, practical implications and technical observations based on the recorded results.

A clear trend was noted across all engine operating points: increasing the ammonia energy share in the fuel blend leads to a systematic and nonlinear decline in overall efficiency, especially above 30–35% NH_3. The largest absolute efficiency drop occurred at a load of 20 Nm, with a 28.05% decrease at 57.16% ammonia, reducing efficiency from 22.57% to 16.24%. At 40 Nm, the maximum efficiency loss was 26.57% at 52.21% NH_3 (final efficiency: 22.27%). For 60 Nm and 51.09% NH_3, efficiency declined from 35.20% to 26.13%, a 25.77% drop. At the highest load, 80 Nm, a reduction from 35.08% to 26.64% (24.06%) was observed with 48.85% ammonia. An interesting anomaly was noted at 80 Nm with a low ammonia share (7.77%), where a slight efficiency increase of 0.6% was recorded. This effect may be attributed to favorable thermal conditions at high load enabling more complete oxidation of a small fraction of ammonia and possibly enhancing radical-driven reactions. However, given the small magnitude of this change it may also fall within the range of experimental uncertainty. Further tests are required to confirm whether this effect is systematic. At high ammonia shares, final efficiency values tend to converge across different loads, indicating that the engine operates with similar efficiency regardless of torque at elevated NH_3 levels, but with clearly higher energy losses compared to pure diesel operation. The efficiency drop is mainly attributed to incomplete ammonia combustion, resulting from its high auto-ignition temperature and lower heating value. A higher NH_3 content leads to more unburned fuel and lower usable energy output. From a practical standpoint, small to moderate ammonia admixtures (up to ~20%) may be environmentally justified, as efficiency losses remain relatively minor and are offset by the reduction in particulate emissions. Additionally, the presence of unburned ammonia in the exhaust may be beneficial for selective catalytic reduction (SCR) systems. As a natural NO_x reductant, ammonia could potentially replace synthetic AdBlue, simplifying emission control systems and lowering operating costs.

4. Future research directions

4.1. Development of a method for measuring ammonia content in exhaust gases

The results of the conducted study demonstrated both the environmental potential of ammonia–diesel co-combustion (primarily in reducing particulate matter emissions) and the limitations stemming from decreased system energy efficiency. Based on these findings, several key areas have been identified for further experimental and development work.

Future research should focus on developing a dedicated analytical method – e.g., using UV-VIS spectrophotometry combined with cuvette tests. One of the main limitations of the current experiment was the inability to directly measure ammonia concentration in the exhaust due to interference with the chemical gas analyzer. The proposed approach includes:

- use of reagents that selectively react with NH_3 in the presence of NO_x and other exhaust components
- standardization of measurements using portable laboratory kits
- calibration of the method against known concentrations, with the possibility of integrating it into a sampling system directly from the exhaust line.

4.2. Optimization of diesel injection strategy

The observed efficiency drop with increasing ammonia share is largely due to inefficient combustion. Therefore, research should be conducted on modifying the diesel injection strategy, aiming to:

- adjust injection pressure and timing for both pilot and main injection events
- adapt the fuel injection control algorithm to the thermal and ignition properties of the diesel–ammonia mixture.

Such modifications could improve ignition quality and reduce the amount of unburned ammonia, thereby increasing overall efficiency.

4.3. Research on ammonia–hydrogen mixtures and use of ammonia decomposition catalysts

The use of hydrogen as a co-fuel or the application of catalysts that decompose ammonia into hydrogen and nitrogen has been proposed in the literature as a means of improving combustion stability and efficiency. Hydrogen's high reactivity can enhance ignition and flame propagation while catalytic decomposition could provide an in-cylinder source of hydrogen. Although not investigated in this study, these strategies represent complementary approaches that may support future development of ammonia-based engine technologies.

5. Conclusions

The experiments on ammonia–diesel co-combustion in a compression-ignition engine demonstrated both advantages and limitations of this approach. A clear decline in overall efficiency was observed as the share of ammonia-derived energy increased, with the most pronounced reductions occurring above approximately 30% ammonia. These efficiency losses reached about 25–30% relative to pure diesel operation and were attributed primarily to the high ignition temperature and low reactivity of ammonia which resulted in incomplete combustion and greater energy losses. At the same time, a consistent decrease in particulate emissions was recorded with increasing ammonia content. Expressed both as FSN and in converted mass units, particulate emissions fell by more than 15% at low loads and by 10–14% at high loads which represents a significant improvement in soot-related exhaust quality. Importantly, even under the least favorable operating conditions, particulate matter levels remained far below the Stage V regulatory limits, suggesting that ammonia–diesel co-combustion can be applied without compromising compliance with current emission standards. The presence of unburned ammonia in the exhaust stream also indicates potential integration with selective catalytic reduction systems where ammonia could act directly as a NO_x reductant, reducing or eliminating the need for additional reagents. From a practical standpoint, moderate substitution of diesel with ammonia, up to around 20% of the energy share appears to be the most promising compromise offering notable emission benefits while limiting efficiency losses to an acceptable level.

Nomenclature

CI	compression ignition
EGR	exhaust gas recirculation
FSN	filter smoke number
LHV	lower heating value
PM	particulate matter
SCR	selective catalytic reduction

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