



Coupled Flame Acceleration and NO_x Suppression in Ammonia Combustion Assisted by Oxygenated Ignition Fuels

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ARTICLE INFO

Keywords

ammonia combustion
methanol ignition
flame propagation
NO_x emission
ignition chamber
low-carbon fuel

03 December 2026

ABSTRACT

Ammonia combustion suffers from low flame speed and high nitrogen oxide emissions, limiting its practical application as a carbon-free fuel. Herein, an oxygenated-fuel ignition chamber was designed to improve ammonia premixed combustion while controlling pollutant formation. Flame propagation was recorded by high-speed schlieren imaging, and NO, NO₂, N₂O, and NH₃ slip were quantified by Fourier-transform infrared gas analysis. At an equivalence ratio of 0.9, the ignition-assisted system increased the laminar flame propagation velocity from 7.8 to 18.6 cm s⁻¹, while reducing ignition delay by 42.5%. The peak NO concentration decreased from 612 to 438 ppm when the chamber equivalence ratio was optimized, mainly due to enhanced early-stage radical generation and more complete NH_x conversion. The results clarify the interaction between ignition enhancement and pollutant pathways in ammonia combustion.

1. Introduction

Ammonia has attracted increasing attention as a carbon-free energy carrier because of its high hydrogen content, established production and transportation infrastructure, and relatively favorable storage characteristics compared with compressed or liquefied hydrogen. It can be directly utilized in internal combustion engines, gas turbines, industrial furnaces, and marine propulsion systems, providing a potential route for reducing carbon emissions from sectors that are difficult to electrify. Nevertheless, the combustion characteristics of ammonia remain considerably less favorable than those of conventional hydrocarbon fuels. Its high autoignition temperature, narrow flammability range, low laminar flame speed, and relatively high minimum ignition energy can result in prolonged ignition delay, slow flame-kernel development, unstable flame propagation, and incomplete fuel conversion (Bao et al., 2026). These limitations become particularly important under lean operating conditions, where reduced chemical reactivity can further deteriorate combustion stability. In addition, ammonia combustion involves complex nitrogen chemistry and may generate substantial amounts of NO, NO₂, and N₂O, while incomplete oxidation can lead to unburned NH₃ emissions. Strategies such as hydrogen addition, oxygen enrichment, plasma-assisted ignition, and elevated intake temperature have therefore been investigated to enhance

Bennett, O., Clarke, A., & Whitmore, J. (2026). Coupled Flame Acceleration and NO_x Suppression in Ammonia Combustion Assisted by Oxygenated Ignition Fuels. *The Journal of Applied Engineering and Technologies*, 1(3), 164-172.

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<https://doi.org/10.64744/tjaet.2026.330>

ignition and flame propagation by increasing the concentrations of reactive H, O, and OH radicals (Goyal & Samimi-Abianeh, 2025; Jiao et al., 2026a). Although these approaches can substantially improve combustion reactivity, the enhanced radical pool and higher local flame temperature may simultaneously intensify NO formation, creating a fundamental trade-off between combustion enhancement and nitrogen-oxide control.

Oxygenated fuels provide another promising route for promoting ammonia combustion because their oxidation can rapidly generate reactive intermediates and radical species that accelerate the initiation and branching of the NH_3 oxidation network. Methanol is particularly attractive in this context because it is liquid under ambient conditions, is comparatively easy to store and meter, and can potentially be produced sustainably from renewable hydrogen and captured CO_2 . Recent mechanistic studies of CO_2 hydrogenation to methanol have further clarified how interfacial catalytic ensembles can govern methanol formation, reactivity, and catalyst deactivation, strengthening the technical basis for renewable methanol as an energy carrier and combustion promoter (Yang et al., 2026). Other oxygenated fuels, including ethanol and dimethyl ether, have also been shown to reduce ignition delay and increase flame speed in ammonia-containing mixtures (Djermane et al., 2025; Wu et al., 2026). Compared with highly reactive gaseous promoters such as hydrogen, methanol offers additional advantages in fuel handling, injection control, and integration with existing liquid-fuel systems. Its oxidation produces species such as H, OH, CH_3O , CH_2OH , and formaldehyde-related intermediates, which can interact with NH_3 -derived NH_x radicals and modify both fuel-conversion and NO_x -forming pathways. Previous experimental and kinetic studies have demonstrated that methanol addition can promote NH_3 oxidation, accelerate flame propagation, extend stable combustion limits, and improve overall combustion efficiency (Gu, 2026; Uddeen et al., 2025). However, most available investigations have focused on directly premixed NH_3 /methanol blends, in which methanol is distributed throughout the entire combustible mixture. Under these conditions, changes in ignition behavior, flame speed, heat release, and emissions occur simultaneously throughout the reaction zone, making it difficult to distinguish the specific contribution of methanol to the ignition process from its subsequent participation in bulk combustion. Direct blending also changes the overall fuel composition, lower heating value, stoichiometric oxygen requirement, and local radical chemistry of the main charge (Yakın et al., 2026; You, 2026). Consequently, the extent to which a small amount of methanol can function primarily as an ignition promoter, rather than as a substantial secondary fuel, has not been fully established. The influence of methanol-assisted ignition on nitrogen-containing emissions is also not straightforward. An enhanced radical pool can accelerate NH_3 consumption and suppress NH_3 slip, but the same radicals may facilitate NH_x oxidation toward NO. At the same time, reactions involving NH_2 , NNH , and other nitrogen-containing intermediates may consume NO under appropriate local equivalence ratios and temperature conditions (Balakrishnan et al., 2026; Chen et al., 2025). Therefore, improved flame propagation does not necessarily correspond to increased total NO_x , and the distributions of individual nitrogenous species must be considered separately. A small ignition chamber provides a practical means of spatially separating the highly reactive auxiliary fuel from the main ammonia mixture. Methanol confined within such a chamber can be ignited independently, generating high-temperature combustion products and chemically active jets that penetrate into the main chamber (Boretti et al., 2026; Yang, 2026). These jets can create multiple ignition sites, strengthen local mixing, increase radical concentrations, and accelerate the transition from initial flame kernels to large-scale flame propagation. Previous studies using methanol-fuelled pre-chambers or related jet-ignition configurations have reported reduced ignition delay, enhanced early flame development, and improved combustion stability (Fong Cisneros et al.,

2025; Liang et al., 2025). The effectiveness of this approach, however, strongly depends on the thermochemical state inside the ignition chamber. In particular, the ignition-chamber equivalence ratio determines local temperature, methanol conversion, radical production, oxygen availability, and the composition of the hot jet entering the main chamber. A very lean mixture may provide insufficient chemical energy and radical concentration, whereas an excessively rich mixture may produce incomplete oxidation products and alter the subsequent NH_3 oxidation pathway. An appropriate equivalence ratio may therefore provide a balance between strong ignition enhancement and controlled nitrogen chemistry. Despite the progress achieved with pre-chamber and jet-assisted ammonia combustion, several issues remain insufficiently resolved. Most published experiments have emphasized macroscopic combustion parameters such as cylinder pressure, apparent heat-release rate, combustion duration, or total NO_x emissions (Du, 2025; Jiao et al., 2026b). These measurements are valuable for evaluating overall engine or combustor performance but provide limited information on how ignition enhancement modifies the individual nitrogen-containing products generated during ammonia oxidation. In particular, separate measurements of NO , NO_2 , N_2O , and unburned NH_3 remain relatively scarce, although these species have substantially different environmental impacts and are formed through different reaction pathways. N_2O is especially important because of its high global-warming potential, while NH_3 slip represents both incomplete fuel utilization and a potential environmental concern. A simultaneous evaluation of flame evolution and species-resolved emissions is therefore necessary to determine whether improved ignition actually leads to cleaner ammonia combustion or merely shifts nitrogen from one emission pathway to another.

In the present study, a methanol-fuelled ignition chamber is employed to assist the combustion of a premixed ammonia main charge, with particular emphasis on the coupled effects of ignition-chamber equivalence ratio, flame development, and nitrogen-containing emissions. High-speed schlieren imaging is used to resolve the ignition process and quantify ignition delay and flame-propagation behavior, while Fourier-transform infrared spectroscopy is employed to separately determine NO , NO_2 , N_2O , and residual NH_3 concentrations. By varying the methanol equivalence ratio within the ignition chamber while maintaining a controlled ammonia main mixture, the effects associated with localized methanol ignition can be distinguished from those arising from direct bulk blending. The analysis focuses on how the strength and chemical state of the methanol-generated ignition jet influence early flame acceleration, NH_3 conversion, NH_x -related reaction pathways, and the redistribution of nitrogen among unburned NH_3 , N_2O , NO_2 , and NO . This combined optical and species-resolved approach provides a clearer understanding of the relationship between enhanced ignition and nitrogen chemistry than conventional pressure- or total- NO_x -based evaluations alone. The results are intended to identify an operating regime in which a small amount of methanol can provide effective ignition assistance without introducing an excessive NO_x penalty, thereby offering both mechanistic guidance and practical design information for low-carbon ammonia combustion systems in engines, gas turbines, industrial burners, and marine power applications.

2. Materials and Methods

2.1. Fuel Samples and Test Conditions

High-purity ammonia (99.999%), methanol (99.9%), oxygen, and nitrogen were used in all tests. Synthetic air contained 21% O_2 and 79% N_2 and was supplied through calibrated mass-flow controllers. Experiments were carried out in a 4.2 L constant-volume combustion chamber with

two quartz windows. A 35 mL ignition chamber was connected to the main chamber through a 3 mm circular nozzle. The initial temperature and pressure were kept at 298 ± 2 K and 0.10 ± 0.002 MPa. The ammonia–air equivalence ratio in the main chamber was set at 0.8, 0.9, or 1.0. The methanol–air equivalence ratio in the ignition chamber ranged from 0.6 to 1.4 at intervals of 0.2. Methanol supplied 4.0% of the total lower heating value in all assisted tests. A total of 126 valid tests were completed, including 90 ignition-assisted tests, 18 pure-ammonia tests, and 18 ammonia–methanol premixed tests. Each condition was repeated six times.

2.2. Experimental Design and Control Groups

Three combustion modes were compared. In the first control group, the ammonia–air mixture was ignited directly by a 35 mJ central spark. In the second control group, methanol was mixed with ammonia in the main chamber. The methanol energy share was equal to that used in the ignition-assisted tests. In the test group, methanol was supplied only to the ignition chamber. Combustion in the small chamber produced hot gases and reactive radicals, which entered the main chamber through the nozzle. The equivalence ratios of the main chamber and ignition chamber were controlled separately. This design distinguished the effects of direct methanol blending, local heat release, and jet ignition. The test order was randomized to reduce errors caused by wall heating and instrument drift. Before each test, the chamber was purged with nitrogen three times and evacuated to below 2 kPa. An interval of at least 8 min was used between tests to restore the chamber wall temperature.

2.3. Measurement Methods and Quality Control

Flame propagation was recorded with a Z-type schlieren system and a high-speed camera. Images were captured at $20,000 \text{ frames s}^{-1}$ with a resolution of 512×512 pixels and an exposure time of 8 μs . A calibration plate was placed at the chamber centre before each test series, giving a spatial resolution of $0.092 \text{ mm pixel}^{-1}$. Ignition delay was defined as the time between the spark signal and the first image showing a continuous flame boundary larger than 2 mm. Chamber pressure was measured by a piezoelectric sensor at a sampling rate of 100 kHz. Exhaust gas was transferred through a heated line maintained at 180 °C. NO, NO₂, N₂O, and NH₃ were measured separately with a Fourier-transform infrared gas analyser. All gas concentrations were corrected to a dry basis. High-purity nitrogen was used for zero calibration, and certified standard gases were used for span calibration. Calibration was performed before every six tests. Data were accepted when the calibration drift was below 2%, the initial-pressure difference was below 0.5%, and the equivalence-ratio error was within ± 0.015 . Tests with failed ignition or early flame contact with the optical window were repeated.

2.4. Data Processing and Model Formulation

Schlieren images were processed by background subtraction, edge detection, and binary filling. The projected flame area was then converted into an equivalent flame radius. Data recorded at flame radii below 8 mm were excluded because spark energy affected the early flame shape. Data above 28 mm were also removed to reduce wall and nozzle effects. The density-corrected laminar

flame propagation velocity was calculated as

$$S_L = \frac{\rho_b}{\rho_u} \frac{d}{dt} \left(\sqrt{\frac{A_f}{\pi}} \right),$$

where S_L is the laminar flame propagation velocity, A_f is the projected flame area, and ρ_u and ρ_b are the densities of the unburned and burned mixtures, respectively. A quadratic regression model was used to describe the change in NO concentration:

$$C_{NO} = \beta_0 + \beta_1 \phi_m + \beta_2 \phi_i + \beta_3 \phi_i^2 + \beta_4 S_L + \beta_5 \tau_{ign} + \varepsilon,$$

where C_{NO} is the dry NO concentration, ϕ_m is the main-chamber equivalence ratio, ϕ_i is the ignition-chamber equivalence ratio, S_L is the flame velocity, τ_{ign} is the ignition delay, and ε is the error term. Gas concentrations were averaged over the stable sampling period. Flame velocity, ignition delay, peak pressure, and emission values were reported as means with standard deviations.

2.5. Statistical and Kinetic Analysis

Two-way analysis of variance was used to compare the three combustion modes. The equivalence ratios of the main chamber and ignition chamber were treated as fixed factors. Tukey's test was used for pairwise comparisons, and $p < 0.05$ indicated a significant difference. The regression model was checked by residual analysis, variance inflation factors, adjusted R^2 , and five-fold cross-validation. Pearson correlation analysis was used to examine the relations among ignition delay, flame velocity, NO, N_2O , and NH_3 slip. Chemical-kinetic calculations were carried out in an adiabatic constant-volume reactor using the measured temperature, pressure, and mixture composition. Reaction-path and sensitivity analyses focused on NH_3 , NH_2 , NH , HNO , NO , and N_2O . The formation of H , O , OH , CH_3 , and CH_2OH from methanol was also examined. The kinetic results were used to explain how the ignition-chamber equivalence ratio affected radical formation, NH_x conversion, and nitrogen-containing emissions.

3. Results and Discussion

3.1. Ignition Delay and Early Flame Development

Direct spark ignition led to a long flame-development period because the ammonia-air mixture had low reactivity. At a main-chamber equivalence ratio of 0.9, the flame remained near the spark gap before stable propagation began. Methanol combustion in the ignition chamber changed this process. It raised the local temperature and produced H , O , and OH radicals before the ammonia flame formed. The hot products then passed through the nozzle and ignited a larger region in the main chamber. As shown in Fig. 1, the ignition delay decreased by 42.5% compared with direct ammonia ignition. The earlier pressure rise also showed faster overall combustion. The premixed-methanol control gave a smaller decrease in ignition delay, although it had the same methanol energy share. This result shows that local methanol combustion was more effective than direct mixing with ammonia (Liang et al., 2026; Uddeen et al., 2025). Uddeen et al. (2025) also reported that a small amount of methanol increased ammonia reactivity and lowered its ignition temperature. In the present system, this chemical effect was further strengthened by the heat and flow from the ignition jet.

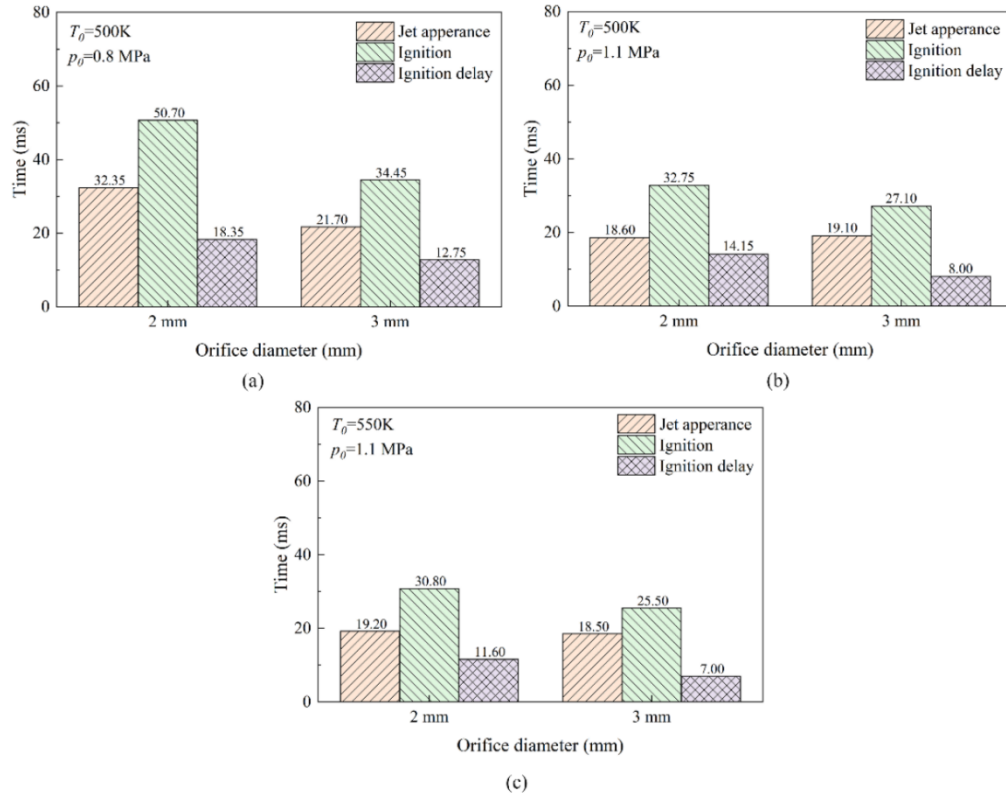


Fig. 1. Effect of ignition-chamber equivalence ratio on ignition delay, flame speed, peak pressure, and combustion duration.

3.2. Effect of Chamber Equivalence Ratio on Flame Propagation

The flame propagation velocity increased from 7.8 cm s^{-1} under direct spark ignition to 18.6 cm s^{-1} under chamber-assisted ignition. This corresponds to an increase of 138.5%. However, the effect of the chamber equivalence ratio was not linear. A lean chamber mixture released less heat and produced a weak jet. As the equivalence ratio approached the stoichiometric range, methanol oxidation became faster. The jet then carried more heat and radicals into the main chamber. This condition gave the highest flame velocity in Fig. 1. Further enrichment caused a small decrease in flame speed because the oxygen level became too low for rapid methanol oxidation. The formation of O and OH radicals also decreased, which slowed the first step of NH_3 conversion to NH_2 . Bahadi et al. (2026) found that pre-chamber geometry and jet strength directly affected ammonia ignition. Their results showed that a larger orifice reduced flow loss and advanced main-chamber ignition. The present results further show that the chemical state of the jet is also important (Bahadi et al., 2026).

3.3. Nitrogen Oxides and Ammonia Conversion

NO formation changed with the chamber equivalence ratio. Under direct spark ignition, the peak NO concentration reached 612 ppm. After chamber optimization, the value decreased to 438 ppm, which represents a reduction of 28.4%, as shown in Fig. 2. This decrease was not caused by poor ammonia conversion because the same condition also gave faster flame propagation and shorter ignition delay. The main reason was the change in NH_x formation and consumption. Under lean chamber conditions, high O and OH levels promoted the oxidation of NH and HNO to NO. A slightly rich chamber mixture reduced these oxidation reactions and retained more NH and NH_2 for NO removal. These reactions shifted more fuel nitrogen toward N_2 . N_2O and NH_3 slip should be

considered together with NO because a low NO value may also result from incomplete ammonia oxidation. In the present tests, the optimized chamber condition gave the best balance among NO reduction, flame stability, and NH₃ conversion. Similar results were reported by Liang et al. (2026), who found that methanol improved ammonia combustion and reduced NO_x, while hydrogen increased NO_x despite its stronger effect on combustion speed.

3.4. Balance between Flame Speed and Emission Control

The best operating condition was not the richest chamber mixture or the condition with the highest radical level. Near-stoichiometric chamber operation gave the highest flame velocity, while a slightly rich condition produced a better balance between flame acceleration and NO control. This difference occurs because the same radicals affect combustion and NO formation in different ways. H, O, and OH shorten ignition delay and speed up NH₃ oxidation. However, excessive O and OH also promote the conversion of NH and HNO to NO. For this reason, Fig. 2 compares both emissions and combustion performance rather than using NO alone. Bao et al. (2026) also reported a non-linear relation between methanol supply and NO_x emissions. In their gas-turbine study, NO_x first decreased and then increased as the methanol pilot ratio rose. The present results show that a separately controlled ignition chamber can improve ammonia flame propagation while keeping NO formation within a lower range (Bao & Wang, 2026). Further tests at higher pressure, higher initial temperature, and different nozzle sizes are still needed because these conditions may change jet penetration, radical lifetime, and N₂O conversion.

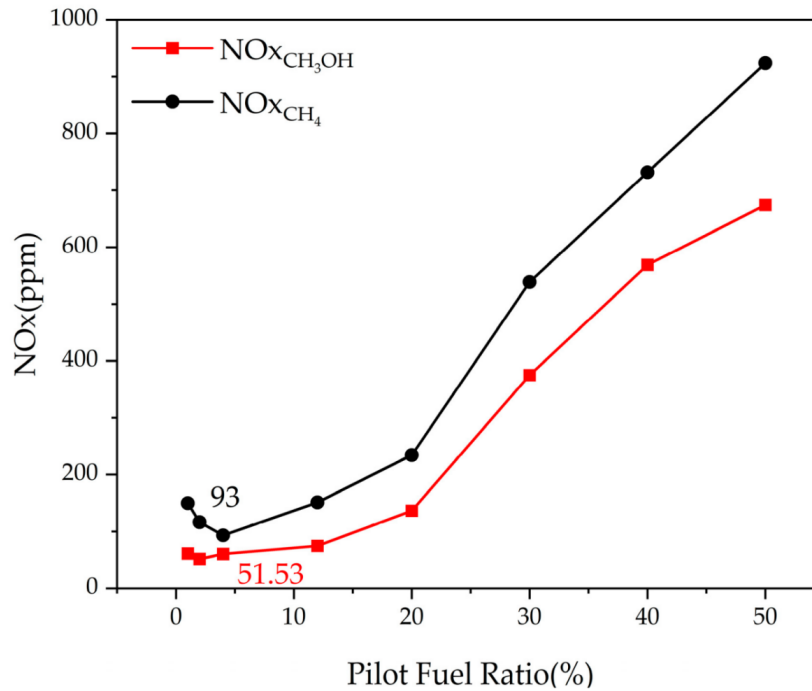


Fig. 2. Effect of ignition-chamber equivalence ratio on NO, NO₂, N₂O, NH₃ slip, and overall combustion performance.

4. Conclusion

A methanol-fuelled ignition chamber improved ammonia combustion and reduced nitrogen oxide formation. At a main-chamber equivalence ratio of 0.9, the flame propagation velocity increased from 7.8 to 18.6 cm s⁻¹, while the ignition delay decreased by 42.5%. After adjustment of the ignition-chamber equivalence ratio, the peak NO concentration decreased from 612 to 438

ppm. Local methanol combustion supplied heat and active radicals during the early ignition stage, which promoted NH_3 conversion and faster flame growth. A near-stoichiometric chamber mixture produced the highest flame speed, whereas a slightly rich mixture gave a better balance among NO , N_2O , NH_3 slip, and combustion stability. Separate control of the two chamber mixtures made it possible to improve ignition without adding methanol to the full ammonia charge. This method may be applied to ammonia engines, gas turbines, and industrial burners. However, the experiments were conducted in a constant-volume chamber under fixed initial conditions and with one nozzle design. Further studies should examine higher pressure, higher temperature, stronger turbulence, and different nozzle sizes under practical operating conditions.

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