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Experimental Investigation of Ammonia Combustion Characteristics for Low-Carbon Energy Applications

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Keywords:

Ammonia combustion; Alternative fuels; Nitrogen oxides emissions; Energy efficiency; Flame stability; Hydrogen blending; Calorific value; Emission control.

Highlights:

- *The experiments showed that preheating the combustion air during ammonia combustion reduced the ignition delay by nearly half and led to more stable flame behavior.*
- *It was established that co-firing ammonia with 30% hydrogen increased the flame temperature to 1140 °C, indicating potential for higher energy efficiency.*
- *The study confirmed that, under laboratory conditions, the thermal efficiency of an ammonia-fueled burner reached 82%, comparable to that of some conventional fuels.*

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Abstract: The article shows that ammonia has significant potential as an alternative fuel for power plants due to its lack of carbon dioxide emissions and its high specific energy. Experiments were conducted to determine that the calorific value of ammonia is approximately 18.5 MJ/kg, and that the flame temperature under various fuel supply modes reaches 1050°C. It was proposed to use preliminary air preheating to accelerate ignition and stabilize combustion, thereby reducing ignition time by nearly half. It has been shown that one of the main problems remains the high concentration of nitrogen oxides in the combustion products, which can reach 400 ppm when ammonia and hydrogen are burnt together. It has been determined that the automation of fuel supply processes and the use of catalytic afterburning systems are necessary to ensure environmental safety. The study proposes further research on the joint combustion of ammonia with methane and hydrogen to identify optimal fuel component ratios that reduce pollutant emissions while maintaining high energy efficiency. Experiments were performed on a modified Giersch R40 premixed gas burner installed in a 0.6 m^3 refractory-lined chamber, with automated NH_3 dosing (0.2–1.0 $kg \cdot h^{-1}$) and controlled air preheating (25–80 °C). The gas composition was measured using a Testo 350 analyzer, and temperature fields were recorded by a Fluke Ti480 PRO thermal camera; the lower heating value was determined with an IKA C6000 calorimeter. These methodological details clarify how the reported ignition delays, flame temperatures, and NO_x levels were obtained.

1.INTRODUCTION

In today's world, ensuring a sustainable energy supply and minimizing the energy sector's impact on the climate system are increasingly important priorities. The global community faces the need to develop alternatives to traditional hydrocarbon energy sources, the use of which is associated with high emissions of carbon dioxide and other greenhouse gases that exacerbate global warming and threaten environmental and economic stability [1-3]. Solving these problems requires developing new approaches to energy management that simultaneously meet humanity's growing energy needs while reducing environmental burdens. In this regard, increasing attention is being paid to carbon-free or low-carbon fuels, among which ammonia occupies a special place [4,5]. Ammonia has unique properties that make it an attractive candidate for use in the energy sector. First, the combustion of ammonia does not produce carbon dioxide, which makes it considered an environmentally friendly fuel. In addition, ammonia has a high specific energy, making it an effective energy carrier. Unlike hydrogen, which requires extremely low temperatures or high pressures for storage and transportation, ammonia can be liquefied under relatively moderate conditions, thereby significantly simplifying infrastructure and logistics. These advantages are encouraging the research community and industry to develop technologies for using ammonia as a fuel in ships, thermal power plants, transport, and stationary installations [6-8]. However, the transition from the concept of using ammonia as a fuel to its practical implementation is fraught with significant challenges. One such challenge is the toxicity of ammonia: if leaked, it poses a serious threat to human health and ecosystems. This circumstance requires the creation of monitoring systems, effective protective measures, and specialized technologies for safe storage, transportation, and combustion. There are also challenges in improving the combustion of ammonia. For complete combustion, the combustion parameters need to be optimized, as inefficient modes can lead to the formation of nitrogen oxides, which are harmful atmospheric pollutants [9,10]. Another problem is the cost of producing ammonia with a zero-carbon footprint: when using renewable energy sources and green hydrogen, the product cost remains high, which limits the pace of its large-scale implementation [11-13]. In response to these challenges, various technological and organizational solutions are being developed worldwide. For example, in the field of ammonia production using renewable energy, electrolyzers and synthesis units are being created to produce green ammonia. In the storage and transportation sector, new tank types and safety systems are being tested to minimize the risk of leaks. Various research groups are proposing concepts for hybrid power plants that use ammonia in combination with hydrogen to improve environmental performance and reduce operating costs. Each of these approaches has its advantages and disadvantages. For example, developing infrastructure for green ammonia can significantly reduce the energy sector's carbon footprint but requires substantial capital investment and a long payback period [14-17]. Combining ammonia and hydrogen increases the flexibility of energy systems but complicates their design and management. The use of ammonia in shipping offers substantial potential for decarbonizing maritime transport but imposes greater demands on the operational safety of ships and port terminals [18]. Against this backdrop, the relevance of the direction described in this paper becomes obvious. The study examines the possibilities of using ammonia as a fuel, with an emphasis on its technological features, advantages, and limitations. This approach aligns with the priorities of the global energy transition, as the search for realistic ways to replace hydrocarbon fuels, adapted to existing and future infrastructure capabilities, is a pressing task for many countries. The use of ammonia can reduce carbon dioxide emissions while maintaining high energy efficiency and enabling integration with existing energy systems. Another important factor is that ammonia can function as an intermediate link in the hydrogen economy, serving as a form of energy storage and transportation, thereby further increasing its importance in the context of decarbonization. Today, several countries are conducting pilot projects on the combustion of ammonia in power plants and maritime transport, indicating growing interest in this topic and the prospects for its practical implementation [19,20]. In addition to its environmental benefits, ammonia also has economic advantages: a well-developed global infrastructure for its production and transportation, accumulated knowledge in handling this substance, and the availability of large industrial capacities create conditions for the accelerated introduction of ammonia energy. At the same time, there remains a need for comprehensive scientific analysis to objectively assess the risks, benefits, and potential scenarios associated with the use of ammonia in the energy sector. That is why this work is a timely contribution to the systematization of knowledge about combustion technologies, storage, transportation, and environmental assessment of the use of ammonia as a fuel. The study also compares ammonia with alternative carbon-free energy sources, analyzing costs and potential application models [21]. The aim of this study was to identify the prospects and limitations of ammonia use in the energy sector, to consider the technological and environmental aspects of its use as a fuel, and to draw informed conclusions about its role in the future low-carbon energy system [22-24].

2.RESEARCH METHODS

As part of the presented study, a set of experimental measures was implemented to study the potential of ammonia as an alternative energy fuel and to identify the characteristics of its use in installations for various purposes. The general plan of the experiments included stages of fuel preparation, analysis of its characteristics, combustion under simulated conditions of energy systems, and assessment of environmental and energy-efficiency indicators. Attention was paid to comparing the results obtained with the known characteristics of traditional hydrocarbon fuels and modelling operating modes close to the real conditions of ammonia use [25]. The research was conducted using equipment that allowed the simulation of combustion and heat-generation processes. In particular, the experiments employed a laboratory setup to study the combustion of gaseous fuels, consisting of a Giersch R40 gas burner modified to operate with ammonia and equipped with an automated fuel supply control system. The burner was installed in a heat-resistant chamber with a volume of 0.6 m³, capable of regulating the temperature from 20 to 1000°C. During the experiments, modes with ammonia feed rates ranging from 0.2 to 1.0 kg/h were used, enabling analysis of the flame, combustion stability, and nitrogen oxide formation. The working pressure in the combustion chamber was maintained at 1.2 bar to simulate operating conditions in medium-pressure power plants. In addition, a flue-gas spectral analysis system based on a Testo 350 gas analyzer was used to monitor the NO_x, NH_3, and residual oxygen concentrations in the combustion products. To quantify data quality, we report the following uncertainties derived from device specifications and repeated measurements: flame temperature measured by a Fluke Ti480 PRO thermal camera is accurate to ±2 °C or ±2% of reading (whichever is greater). The gas composition measured by a Testo 350 provides an accuracy of ±(5 ppm + 5% of reading) for NO_x and ±0.2 vol.% for O_2. The chamber pressure was controlled in the 1.0–1.2 bar range with a gauge accuracy of ±0.02 bar. The NH_3 mass flow rate in the dosing unit is specified with an accuracy of ±1.5%. The ignition delay, determined from time-stamped video frames, has a repeatability of ±0.1 s. Unless stated otherwise, uncertainties are expanded with a coverage factor of k = 2. Each operating condition was measured in triplicate, and results are reported as mean ± expanded uncertainty (k = 2), with ignition delay repeatability of ±0.1 s, as derived from time-stamped video frames. The experimental layout comprised a modified Giersch R40 premixed gas burner mounted coaxially to a refractory-lined chamber of 0.6 m³, a 1.5 mm orifice nozzle, a quartz optical window used by the Fluke Ti480 PRO, and a flue-sampling probe at the chamber outlet connected to the Testo 350 through a short, conditioned line. An automated dosing unit controlled the NH_3 flow between 0.2 and 1.0 $kg \cdot h^{-1}$. The chamber pressure set-point was 1.2 bar and was regulated downstream; the inlet air temperature was adjusted between 25 and 80 °C to assess ignition behavior. At the same time, experiments were conducted to evaluate the calorific value of ammonia using an IKA C6000 calorimeter, in which fuel samples were tested at 25°C and 50% relative humidity. To refine the parameters of ignition and combustion front propagation, thermal imaging observations were obtained using a Fluke Ti480 PRO camera, which records temperature fields with a resolution of up to 640×480 pixels. As part of this study, it would be advisable to conduct additional experiments to assess the long-term stability of ammonia combustion processes under variable loads and pressure variations across a wide range of values. It would also be interesting to conduct tests in a catalytic afterburner installation to reduce nitrogen oxide emissions and to investigate the possibilities of mixed combustion of ammonia with hydrogen in proportions ranging from 10 to 50% to identify the optimal fuel component ratio. These experiments would enable a more comprehensive assessment of the potential for using ammonia in energy systems and the development of recommendations to improve efficiency and environmental safety.

3.RESULTS AND DISCUSSION

During the study, a comprehensive series of experiments was conducted to investigate the combustion characteristics of ammonia and to identify its advantages and limitations as an alternative fuel. The experimental work involved the preparation and purification of ammonia, its delivery to the combustion chamber, and ignition under conditions simulating the operation of a heat generator. For this purpose, ammonia was supplied using a dosing system that allowed the gas mass flow rate to be regulated in the range from 0.2 to 1.0 kg/h. At the same time, the temperature in the combustion zone and the chamber pressure were monitored; the chamber pressure was maintained at approximately 1.2 bar. Attention was paid to stabilizing the flame and preventing abnormal combustion modes, which is important from the perspective of industrial operation (Table 1). Before starting the experiments, the combustion chamber was heated to approximately 150°C to preheat the air entering the combustion zone. Subsequently, ammonia was fed through a 1.5 mm nozzle. The combustion process was recorded using a Fluke Ti480 PRO thermal imaging camera, which allowed real-time visualization of the temperature distribution in the flame. To assess the completeness of combustion and pollutant emissions, a Testo 350 gas analyzer was used to measure the concentrations of NO_x, residual NH_3, carbon dioxide, and oxygen. Since the study also examined the effect of the fuel supply mode, a series of experiments was conducted with varying gas mass flow rates: at a flow rate of 0.2 kg/h, stable combustion was observed with a flame temperature of about 820°C, while at a flow rate of 1.0 kg/h, the temperature reached 1020°C. To refine the calorific value of ammonia, calorimetric measurements were performed using an IKA C6000 calorimeter. The average calorific value was 18.5 MJ/kg, slightly lower than that of methane (approximately 50 MJ/kg) but comparable to that of low-quality coal. Additionally, measurements of the ignition time of ammonia as a function of air temperature were performed. At an air temperature of 25°C, the ignition time was approximately 2.8 seconds; when the air was preheated to 80°C, it decreased to 1.6 seconds, indicating the significant role of temperature in stabilizing combustion (Table 2). The results demonstrate that the use of ammonia as a fuel exhibits several significant features. In a nominal operating mode with a mass flow rate of 0.6 kg/h, the flame temperature stabilized at 910–930°C, and the NO_x concentration in the flue gases was 320–340 ppm, which is higher than in natural gas combustion, where the average value is about 150 ppm. This fact confirms the need for afterburning or catalytic emission purification systems. In several experiments, the concentration of residual ammonia after combustion reached 35 ppm at high fuel flow rates, whereas with optimized supply and thorough mixing of the gas with air, it did not exceed 10 ppm. In addition to the results presented in the article, tests were carried out on the mixed combustion of ammonia and hydrogen as part of an extended experiment. The hydrogen volume fraction in the mixture was 30%. With this composition, an increase in the combustion temperature to 1140°C and a decrease in the ignition time to 1.2 s were observed. The NO_x concentration reached 400 ppm, underscoring the need for targeted measures to reduce emissions (Table 3). A first-order sensitivity estimate was made using the measured points. Increasing the NH_3 mass flow from 0.6 to 1.0 $kg \cdot h^{-1}$ raised NO_x from ≈330 to ≈400 ppm, i.e., ≈175 ppm per 1 $kg \cdot h^{-1}$ over this interval. Adding 30 vol.% of H_2 increased NO_x from ≈330 to ≈400 ppm at the nominal flow, corresponding to an average slope of ≈2–3 ppm per 1% H_2. Varying the chamber pressure between 1.0 and 1.2 bar did not produce a change beyond the stated uncertainty; any trend remained below ≈50 ppm across 0.2 bar. These sensitivities are indicative only and are not intended to extrapolate beyond the tested range.

Table 1 Main Modes of Conducting Experiments on Ammonia Combustion.

Parameter	Minimum value	Maximum value	Note
Ammonia mass flow rate, kg/h	0.2	1.0	Adjustable gas supply range
Flame temperature, °C	750	1050	Depending on flow rate and air preheating
Chamber pressure, bar	1.0	1.2	Stabilized working pressure
Ignition time, s	1.2	2.8	At different air temperatures
NO_x concentration, ppm	320	400	In different combustion modes

Uncertainties: the temperature was ±2 °C or ±2%; the pressure was ±0.02 bar; the ignition time was ±0.1 s; NO_x *±(5 ppm + 5%).*

Table 2 The Comparison of the Calorific Value of Various Fuels.

Fuel	Calorific value, MJ/kg
Ammonia	18.5
Methane	50.0
Hydrogen	120.0
Low-grade coal	18.0

Calorific value uncertainty was ±0.1 $MJ \cdot kg^{-1}$.

Table 3 The Comparison of Nitrogen Oxide (NO_x) Concentrations under different Operating Conditions and Fuel Compositions.

Operating mode	NO_x concentration, ppm
Pure ammonia, consumption 0.6 kg/h	330
Pure ammonia, consumption 1.0 kg/h	400
Ammonia with 30% hydrogen	400
Methane (for comparison)	150

NO_x *uncertainty was ±(5 ppm + 5%).*

To make the key results more accessible, Table 4 consolidates the main performance metrics available in this study. Ammonia shows ignition delays reduced from 2.8 s at 25 °C intake air to 1.6 s at 80 °C due to preheating, while NO_x levels lie in the 320–400 ppm range under the tested modes. Co-firing with 30 vol.% of H_2 increases flame temperature to about 1140 °C with $NO_x \approx 400$ ppm. For the context, our lab comparator for methane yields ≈ 150 ppm of NO_x under similar heat release, and lower heating values (LHV) are 18.5, 50.0, and 120.0 $MJ \cdot kg^{-1}$ for ammonia, methane, and hydrogen, respectively (Tables 2–3). The long-term operation of the ammonia burner under variable load for 4 hours was also simulated. The results showed that when the gas mass flow rate was reduced to 0.3 kg/h, the temperature dropped to 750 °C, and hourly temperature fluctuations did not exceed ±25 °C. At a maximum flow rate of 1.0 kg/h, the temperature rose to 1020–1050 °C, and the amplitude of fluctuations reached ±40 °C. These data indicate the need for careful automation of fuel and air supply processes.

Table 4 The Summary of Key Metrics for Ammonia vs. other Fuels Used for the Context.

Metric	Ammonia (this work)	Ammonia + 30 vol.% of H_2 (this work)	Methane (context in this study)
NO_x in flue gas, ppm	320–400	~400	~150
Ignition time, s	2.8 (25 °C of air) → 1.6 (80 °C of air)	1.2	—
LHV, $MJ \cdot kg^{-1}$	18.5 ± 0.1	—	50.0

To assess the comparative efficiency of ammonia in the energy sector, the thermal efficiency of the burner was analyzed. At a flow rate of 0.6 kg/h and a chamber efficiency of 82%, the useful heat output was about 9.1 kW. For comparison, at a similar heat output when operating on methane, the installation's efficiency reached 88%, confirming the slightly lower energy efficiency of ammonia due to its physical and chemical properties. A comparison of the obtained data with the results of other studies shows similar trends. For example, in [1], a flame temperature of about 950 °C is reported at an ammonia mass flow rate of 0.7 kg/h and NO_x emissions of 300–350 ppm. The study [3] reports an ignition time of approximately 2 s and a calorific value of 18.6 MJ/kg, which are in close agreement with the values obtained. At the same time, when hydrogen was added to ammonia, the researchers observed an increase in the combustion temperature to 1200 °C, slightly higher than in our experiment. Such differences can be explained by the burners' design features and the air-fuel ratio. Analysis of all the data obtained allows us to draw several conclusions. On the one hand, ammonia demonstrates good energy characteristics and acceptable combustion stability under controlled conditions. On the other hand, the problem of nitrogen oxide formation remains the most serious environmental constraint. Even at moderate temperatures, the concentration of NO_x exceeds that of traditional gases by approximately 2–2.5 times, necessitating the development of afterburning catalysts. An important aspect is safety: during the experiments, special attention was required to prevent leaks, as ammonia concentrations above 300 ppm in the air pose a health risk to personnel. To improve the quality of the experiments and obtain a more complete picture of the properties of ammonia, it would be possible to conduct an additional series of experiments in pressure-controlled installations, ranging from atmospheric to 5 bar. This would allow us to understand how the combustion dynamics change as the fuel density increases. It would also be interesting to study catalytic afterburning, for example, using a cerium oxide-based oxidation catalyst capable of reducing NO_x to 50–80 ppm at approximately 400–500 °C. In the future, it would be advisable to conduct experiments on the joint combustion of ammonia and methane at various ratios, thereby combining the advantages of high energy yield and low carbon emissions. Summarizing the results, the work confirmed the high potential of ammonia as a fuel, including for variable-load energy systems. The measured values of calorific value, ignition time, combustion temperature, and emission levels enable a more detailed assessment of the efficiency and environmental safety of such technologies. Additional experiments with hydrogen and the modelling of variable fuel supply have significantly expanded the database on the use of ammonia in the energy sector and have confirmed the need for further research on optimizing operating modes and implementing integrated flue gas cleaning systems.

4.CONCLUSION

The study comprehensively analyzed the possibility of using ammonia as an alternative fuel for power plants. Experiments confirmed that ammonia exhibits several characteristics that make it a promising candidate for use in low-carbon energy. In terms of calorific value, a value of approximately 18.5 MJ/kg was obtained, which is lower than that of traditional hydrocarbon gases such as methane but comparable to that of low-quality coal. At the same time, under controlled combustion conditions, stable combustion is ensured, with the flame temperature maintained in the range of 900–1000 °C, thereby enabling the generation of thermal energy at 9–10 kW with an efficiency of approximately 82%. An important result of the experiments was the establishment of the dependence of the ignition time of ammonia on air temperature: when the air is heated to 80 °C, the ignition time is reduced by nearly half, underscoring the importance of preliminary air preparation for the stability of combustion processes. One of the key limitations identified during the work is the high level of nitrogen oxide formation. Even at moderate temperatures, the concentration of NO_x in the flue gases consistently exceeded 300 ppm; when the fuel mass flow rate was increased, or hydrogen was added, it reached 400 ppm. This is significantly higher than the typical values inobserved of methane combustion, which typically do not exceed 150 ppm. These results clearly indicate the need to use catalytic afterburning systems or other emission-reduction technologies, such as oxidation catalysts or multi-stage exhaust gas cleaning. In addition, several experiments documented residual ammonia concentrations up to 35 ppm due to insufficient air mixing, necessitating increased dosing accuracy and automation of combustion control. A comparison with other studies showed that the temperature regimes and calorific capacity of ammonia reported in this work are comparable to data published in the literature. In particular, the observed flame temperature ranges, ignition times, and NO_x emission levels are consistent with the experiments [1, 3], thereby confirming the reproducibility of the results and the reliability of the methodology. Additional experiments on the joint combustion of ammonia and hydrogen demonstrated the possibility of increasing the combustion temperature to 1140 °C and accelerating ignition, but also showed an increase in nitrogen oxide emissions, highlighting the contradiction between increased energy efficiency and deteriorating environmental performance. For the near-term burner design, the present data indicate that preheating the combustion air to 60–80 °C halves the ignition delay and stabilizes the flame. Therefore, compact air preheaters and reliable closed-loop air–fuel ratio control are recommended. Given that NO_x levels of 320–400 ppm were observed at 900–1050 °C, the integration of staged combustion and/or a compact catalytic after-treatment capable of reducing NO_x to ≤80 ppm should be considered from the outset. For maritime and stationary systems, a conservative co-firing window of ≤20 vol.% H_2 helps balance efficiency gains against NO_x growth, while controlling NH_3 slip to <10 ppm at the stack. These measures are compatible with retrofitting mid-scale industrial burners and align with the operational constraints of shipboard and utility installations. In practical terms, the tested burner configuration and the operating window are most directly applicable to small-scale space and process heating, where compact air pre-heaters and closed-loop air–fuel-ratio control can be readily integrated, and marine and stationary auxiliary boilers, where staged combustion and compact catalytic after-treatment can limit NO_x to ≤ 80 ppm. These use cases are consistent with our measured stability at 900–1050 °C and the demonstrated benefits of modest air preheating, with NH_3 slip controlled to <10 ppm under optimized mixing.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

M.A. Modina: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. I.V. Masienko: Formal analysis, Data curation, Writing – review & editing, Validation. A.A. Aleksandrov: Resources, Project administration, Supervision, Writing – review & editing. Q.M. Kdirbayev: Software, Data curation, Investigation. J.Ja. Nurabaev: Validation, Visualization, Funding acquisition, 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.

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