

Plasma-Assisted Ammonia Conversion: Mechanisms, Reactor Physics and Emerging Directions

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Abstract. Ammonia (NH₃) is a key nitrogen-containing compound with significant environmental and energy implications. Its emission from agricultural, industrial and waste treatment processes contributes to air pollution and secondary aerosol formation. At the same time, ammonia is increasingly recognized as a carbon-free hydrogen carrier. Non-thermal plasma (NTP) technology has emerged as a promising approach for both ammonia removal and decomposition due to its ability to activate stable molecules under mild conditions. This review presents a comprehensive overview of plasma-assisted ammonia conversion, focusing on reaction mechanisms, plasma physics fundamentals, reactor configurations and recent developments. Particular attention is given to the roles of electron energy distribution, reactive species generation and plasma-catalytic coupling. The challenges associated with energy efficiency, by-product control and scale-up are critically discussed. Finally, future research directions are proposed, highlighting the integration of plasma with catalysis and renewable energy systems.

Keywords: Ammonia; plasma-assisted; in your paper.

1. Introduction

Ammonia (NH₃) is widely emitted from livestock farming, fertilizer usage, and various industrial processes, making it one of the most prevalent nitrogen-containing pollutants in the atmosphere. Its environmental impact is multifaceted, including contributions to particulate matter formation and ecosystem eutrophication. In addition to its environmental relevance, ammonia has gained increasing attention as a potential hydrogen carrier due to its high hydrogen content and ease of liquefaction [1 – 3]. This dual role of ammonia as both a pollutant and an energy vector has stimulated growing interest in advanced technologies for its conversion and removal.

Traditional ammonia abatement technologies, including absorption, adsorption, biofiltration and thermal oxidation, often suffer from high energy consumption, secondary pollution or limited efficiency under fluctuating conditions [4–6]. In this context, non-thermal plasma (NTP) has emerged as a promising alternative due to its ability to generate energetic electrons and reactive species at near-ambient temperatures. Unlike thermal processes, NTP selectively energizes electrons rather than the bulk gas, enabling efficient activation of stable molecules such as NH₃, N₂ and O₂ [7 – 9].

Recent advances in plasma science have expanded the application of NTP beyond pollutant removal to include ammonia decomposition for hydrogen production, nitrogen fixation and plasma catalysis. These developments have been driven by improvements in power supply design, reactor

configurations and diagnostic techniques. Consequently, a detailed understanding of plasma-assisted ammonia conversion processes is essential for optimizing performance and enabling industrial implementation [10–12].

2. Reaction Mechanisms and Plasma Chemistry

The degradation and conversion of ammonia in non-thermal plasma systems are governed by complex plasma chemistry involving electron-driven reactions and radical-mediated pathways. Energetic electrons generated in the plasma collide with ammonia molecules, leading to dissociation and ionization processes. The primary electron-impact reactions involve the cleavage of N–H bonds, forming reactive intermediates such as NH_2 , NH and H radicals [13 – 15]. These intermediates subsequently participate in a network of reactions that ultimately determine product distribution.

The formation of reactive oxygen species (ROS) and reactive nitrogen species (RNS) plays a crucial role in ammonia conversion, particularly in air or oxygen-containing plasmas. Species such as atomic oxygen, hydroxyl radicals and ozone contribute to oxidative pathways, while excited nitrogen species influence nitrogen recombination processes [16–18]. The interaction between these species leads to multiple competing pathways, including complete conversion to nitrogen and water as well as the formation of undesired by-products such as NO_x and N_2O .

The electron energy distribution function (EEDF) is a key parameter controlling plasma chemistry. It determines the probability of various collision processes and thus strongly influences reaction pathways and selectivity. Low-energy electrons are generally associated with efficient ammonia dissociation, whereas high-energy electrons tend to promote the formation of nitrogen oxides [19–21]. Therefore, tailoring the EEDF through power modulation and reactor design is critical for optimizing ammonia conversion efficiency.

Kinetic studies have revealed that NH_2 radicals act as key intermediates in ammonia decomposition, governing the transition from NH_3 to N_2 . The recombination of nitrogen-containing radicals leads to the formation of molecular nitrogen, which is the desired end product in most applications. However, in oxygen-rich environments, competing oxidation reactions may lead to the formation of NO and NO_2 , reducing selectivity and posing environmental concerns [22 – 24].

3. Plasma Reactor Physics and Operational Parameters

The performance of plasma-assisted ammonia conversion is strongly influenced by reactor design and operating conditions. Among various plasma sources, dielectric barrier discharge (DBD) reactors are the most widely used due to their stable operation, uniform plasma distribution and scalability [25–26]. In DBD systems, the presence of dielectric barriers prevents arc formation and enables the generation of non-equilibrium plasma characterized by high electron temperature and low gas temperature.

The input power is one of the most critical parameters affecting plasma behavior and ammonia conversion. Increasing power enhances electron density and reactive species generation, leading to higher conversion efficiency. However, excessive power input may also promote the formation of undesired by-products and reduce energy efficiency [27–28]. Therefore, an optimal power range must be identified for each reactor configuration.

Gas flow rate and residence time are equally important parameters. Higher flow rates reduce the residence time of ammonia molecules in the plasma region, leading to lower conversion efficiency. Conversely, excessively long residence times may result in energy wastage and secondary reactions. The interplay between flow dynamics and plasma kinetics must be carefully balanced to achieve optimal performance [29–30].

Pulse modulation of the power supply has been widely investigated as a strategy to improve plasma efficiency. Parameters such as pulse frequency and duty cycle influence the temporal

evolution of plasma and electron energy distribution. Moderate pulse frequencies can enhance discharge uniformity and increase effective collision frequency, whereas excessively high frequencies may reduce energy per pulse and limit reaction efficiency [31,32].

Humidity and gas composition also significantly affect plasma chemistry. The presence of water vapor promotes the formation of hydroxyl radicals, which are highly effective in ammonia oxidation. However, excessive moisture may quench plasma and reduce electron energy. Similarly, oxygen concentration influences the balance between oxidation and reduction pathways, affecting both conversion efficiency and by-product formation [33,34].

4. Recent Advances and Emerging Trends

Recent research has focused on plasma-catalytic systems that combine the advantages of non-thermal plasma and heterogeneous catalysis. In such systems, plasma-generated reactive species interact with catalyst surfaces, enhancing reaction rates and selectivity. Catalysts based on transition metal oxides, zeolites and noble metals have been extensively studied, demonstrating significant improvements in ammonia conversion and suppression of NO_x formation [35,36].

Another emerging direction is plasma-assisted ammonia decomposition for hydrogen production. Compared with conventional thermocatalytic processes, plasma-driven systems can operate at lower temperatures and offer rapid response times. The synergy between plasma activation and catalytic surfaces enables efficient hydrogen generation while minimizing energy consumption [2,37].

Multi-field coupling technologies have also gained attention, including the integration of plasma with photocatalysis, electrochemical systems and adsorption processes. These hybrid approaches aim to enhance energy efficiency and achieve selective conversion by leveraging complementary mechanisms [38,39]. In addition, the treatment of complex gas mixtures containing ammonia and other pollutants such as VOCs and H₂S is becoming an important research topic, reflecting real-world applications [40].

Despite these advances, several challenges remain. Energy efficiency remains a major limitation, with many plasma systems exhibiting high specific energy consumption. The control of by-products, particularly NO_x, is another critical issue that requires further investigation. Moreover, the scale-up of plasma reactors for industrial applications presents significant engineering challenges related to uniformity, stability and cost.

5. Conclusions and Perspectives

Non-thermal plasma technology offers a versatile and effective approach for ammonia conversion, enabling both pollutant removal and hydrogen production under mild conditions. The unique characteristics of plasma, including non-equilibrium electron energy distribution and rich reactive chemistry, provide opportunities for controlling reaction pathways and enhancing efficiency.

However, the widespread application of plasma-assisted ammonia conversion is still hindered by several challenges, including high energy consumption, limited selectivity and difficulties in scaling up. Future research should focus on optimizing plasma-catalytic systems, improving power supply efficiency and developing advanced reactor designs. In addition, a deeper understanding of plasma chemistry and reaction kinetics is essential for achieving selective conversion and minimizing by-products.

The integration of plasma technology with renewable energy sources and emerging catalytic systems is expected to play a crucial role in the transition toward sustainable energy and environmental systems. With continued interdisciplinary efforts, plasma-assisted ammonia conversion has the potential to become a key technology in both pollution control and hydrogen economy.

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