Research Progress of Hydrogen/Ammonia Gas Turbine Combustion Chambers

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Abstract. Ammonia/hydrogen mixed fuel is important for the deep decarbonization of gas turbines. However, the combustion characteristics of the mixed fuel are at two opposite extremes: the highly reactive hydrogen is easily flashback; the less reactive ammonia has poor flame stability and high fuel nitrogen oxide emissions. In this paper, the basic combustion chemistry of the ammonia-hydrogen mixture is systematically reviewed, and three kinds of combustion technology, the swirl-stabilized combustion, the micro-mixing combustion and the staged combustion, are evaluated, with attention focused on the flame stabilization, the flashback prevention and the organization of low nitrogen oxide combustion. The swirl stabilization is able to anchor the ammonia flame by forming a strong recirculation zone. The micro-mixing combustion provides an effective physical barrier to prevent the flashback, and is suitable for high hydrogen mixing ratio. The staged rich-lean combustion is able to achieve significant nitrogen oxide reduction of decoupling the fuel nitrogen conversion in the rich stage from the combustion in the lean stage, and as low as 54 10-6 (54 ppm, 15% O2) under the optimum conditions. This work gives the theoretical basis of the development of zero-carbon burner, and supports the development of the cleaner gas turbine combustion technologies.

1 Introduction

The profound transition of the global energy system towards carbon neutrality imposes revolutionary demands on the cleanliness and fuel flexibility of power equipment. As a core power device for electricity generation, marine propulsion, and industrial drives, the innovation of gas turbine combustion technology is a critical link in achieving deep decarbonization across the entire industry. Zero-carbon fuels, represented by hydrogen (H_2) and ammonia (NH_3), are regarded as ideal alternatives to traditional fossil fuels because their combustion products do not contain carbon dioxide. However, existing mature gas turbine combustion technologies are primarily optimized for hydrocarbon fuels like natural gas. When confronted with hydrogen and ammonia, whose physicochemical properties are drastically different, these technologies exhibit severe incompatibility. How to modify or redesign the combustion methods for ammonia/hydrogen fuels to simultaneously ensure operational safety and stability, as well as clean and low-carbon emissions, has become the primary technical bottleneck restricting the large-scale application of zero-carbon fuels.

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Systematically reviewing the cutting-edge progress in this field is of urgent practical significance for promoting the research and development of next-generation power equipment.

This paper focuses on key concepts in gas turbine combustors, including "flame stabilization," "flashback", "thermoacoustic oscillation", "lean premixed combustion", and "staged combustion", to investigate the operational performance of ammonia/hydrogen gas turbines under various conditions.

To achieve the efficient and clean utilization of ammonia/hydrogen fuels in gas turbines, current research has formed clear technical pathways, with a core focus on resolving the contradiction of "hydrogen's propensity for flashback, ammonia's difficulty in burning, and the need to control NOx from both." On one hand, addressing combustion stability has led to a strategy combining "physical prevention and control" with "chemical synergy." For hydrogen's high reactivity, micro-mixing combustion technology, which physically divides the flame into numerous miniature flames to effectively enhance flashback resistance, has become a mainstream solution. However, its applicable hydrogen blending ratio typically has an upper limit (e.g., approximately 65%) [1]. For ammonia's low reactivity, the mainstream method is hydrogen blending to aid combustion, supplemented by technologies such as strong swirl and staged combustion to enhance flame stability. Recent studies have shown that pure ammonia can also achieve stable combustion in combustors with a specific high swirl number (e.g., a swirl number of 3.3. On the other hand for NOx emission control staged combustion particularly the "rich-lean" two-stage stratification strategy, demonstrates unique advantages [2, 3]. Research confirms that within the rich-burn first stage, fuel-bound nitrogen is more inclined to be reduced to N_2 rather than oxidized to NO. Latest numerical simulations indicate that by adopting this strategy, with optimized parameters (e.g., 35% hydrogen blending ratio, pressure, and equivalence ratio), NOx emissions can be reduced to an ultra-low level of ~54 ppm. However, the hydrogen blending ratio requires precise control, as excessively high (e.g., >60%) or too low ratios can both lead to a sharp increase in NOx [3].

This paper aims to systematically elaborate on the current synergistic control technologies for flame stability and low NOx in gas turbine combustors fueled by ammonia/hydrogen mixtures. The structure of this paper follows a logic from problem tracing, to technological deconstruction, and finally to practical considerations, hoping to provide a contribution to the field's development with an article possessing both theoretical depth and a realistic perspective.

2 Basic combustion characteristics of ammonia/hydrogen fuels

Hydrogen and ammonia, as zero-carbon fuels, exhibit combustion characteristics at opposite ends of the spectrum, which fundamentally determines the unique challenges faced in combustor design. Understanding their fundamental properties is a prerequisite for subsequent technological development.

2.1 Comparison of key physicochemical parameters of hydrogen and ammonia

Hydrogen is a highly reactive fuel, characterized by a high lower heating value of up to 120 MJ/kg, an extremely fast laminar burning velocity reaching 2.91 m/s under stoichiometric conditions a very short ignition delay time, a high auto-ignition temperature of 844 K, and an exceptionally wide flammability limit. These physicochemical properties result in intense combustion reactions and concentrated energy release, but also make it highly prone to flashback and thermoacoustic oscillations. In contrast, ammonia is a typical low-reactivity fuel with a relatively low heating value of approximately 18.6 MJ/kg an extremely slow laminar burning velocity of only about 0.07 m/s at maximum under atmospheric pressure a higher auto-ignition temperature of around 924 K, and a comparatively narrow flammability limit. These characteristics directly lead to difficulties in ignition, weak flame propagation, and poor stability. When the two are mixed, the physicochemical properties of the fuel exhibit nonlinear variations rather than a simple linear superposition.

2.2 Basic combustion chemical mechanisms of hydrogen and ammonia

Hydrogen and ammonia represent the two extremes of combustion chemistry—"fast" versus "slow." Hydrogen combustion is driven by an efficient chain-branching reaction system, centered on the reaction $H + O_2 = O + OH$. This reaction consumes one H radical while producing two new highly reactive radicals (O and OH), triggering an exponential growth in radical concentration. This allows hydrogen combustion to be completed within an extremely short time, resulting in a highly concentrated radical pool (H, O, OH) and an exceptionally fast reaction rate. Ammonia combustion, by contrast, begins with a stepwise dehydrogenation process of N-H bonds: $NH_3 \rightarrow NH_2 \rightarrow NH \rightarrow N$. Each step requires breaking stable N-H bonds, leading to an overall slow reaction rate. The key intermediate products—NH_2 and NH radicals—serve as the starting point for all subsequent reactions, and their fate directly determines whether the final products are clean or polluting.

2.3 Coupled combustion of hydrogen-ammonia fuel

In pure ammonia combustion, the reaction process is mainly controlled by the stepwise breaking of N-H bonds and the mutual transformation between nitrogen-containing intermediates - this is a relatively slow "nitrogen chemistry" system. When hydrogen is added, the importance of the hydrogen-oxygen reaction system rapidly increases, gradually becoming the core driving the entire combustion process, while the reactions between nitrogen-containing substances play a secondary role. The fundamental driving force for this transformation lies in the chain branching reaction of hydrogen, $H + O_2 = O + OH$. For each H radical consumed in this reaction, two new active radicals (O and OH) are generated, which can significantly increase the concentrations of H, O, and OH radicals in an extremely short time, establishing a high-concentration radical atmosphere that cannot be achieved in pure ammonia combustion. The existence of this high-concentration radical environment fundamentally changes the consumption mode of ammonia. Ammonia is no longer mainly dependent on its own slow decomposition but is rapidly "disassembled" through the path $NH_3 + OH = NH_2 + H_2O$. At the same time, the NH_2 and other nitrogen-containing radicals produced by ammonia decomposition are more inclined to react with OH rather than mainly transforming among nitrogen-containing species as in pure ammonia combustion. It should be noted that the addition of hydrogen does not create new reaction pathways. Studies such as the Mathieu mechanism and the Klippenstein mechanism have shown that the basic reaction steps experienced by ammonia before and after hydrogen addition have no essential differences. The role of hydrogen is to "accelerate" rather than "redirect" - it significantly increases the concentration of radicals, thereby simultaneously enhancing the rates of all existing reaction pathways.

3 The law of different conditions affecting the combustion characteristics of hydrogen-ammonia fuel

3.1 The effect of hydrogen blending ratio on ammonia/hydrogen fuel combustion

The reactivity and high adiabatic flame temperature of hydrogen, if blend hydrogen into ammonia, will increase the laminar burning velocity and adiabatic flame temperature of the mixture, make ignition delay time shorter and make the flammability limits of the mixture wider [4-6]. According to the result of Valera-Medina et al. (2017), when the hydrogen blending ratio is about 40%, the burning velocity of the ammonia-hydrogen mixture is in the same level as the natural gas [7]. This means that the ammonia-hydrogen mixture can reach the design operating conditions of the existent combustors and it is a way possible for stable combustion of ammonia.

3.2 The effect of pressure and equivalent ratio on ammonia/hydrogen fuel combustion

With the pressure increasing, the laminar burning velocity of ammonia-hydrogen mixtures increases a lot, especially at larger hydrogen blending ratio, meaning that the characteristic of fast reaction of hydrogen is strengthened (see Fig. 1). On the one hand, under the pressure increased, the flame propagates much vigorously, and therefore improves the resistance of blow-off and the stable running range of the flame. On the other hand, the pressure increased will decrease the physical residence time of the gas flow in the combustor, which will put the requirement of the rapid and uniform mixing of the fuel and air in the limited time and space more strictly. The equivalent ratio is the direct "valve" which controls the combustion intensity. Near the chemically appropriate ratio ($\Phi \approx 1.0$-1.05), the flame temperature is at the peak, the chemical reaction rate is the fastest, and the flame stability and combustion efficiency are usually the highest. When move in the lean flame direction ($\Phi<1$), the cooling effect of the excess air reduces the flame temperature. Though it is good for the control of the heat load, it is also the wrong place of weakening flame, reduces the reaction rate, gradually approaches the lean flame flameout limit, reduce the flame stability. When moving towards the rich combustion direction ($\Phi>1$), an oxygen deficiency environment will also suppress the reaction rate and may cause the unevenness of the flame temperature distribution due to the incompletely combustion [8, 9]. Fig. 2 shows Variations in laminar flame velocity at different equivalent ratios.

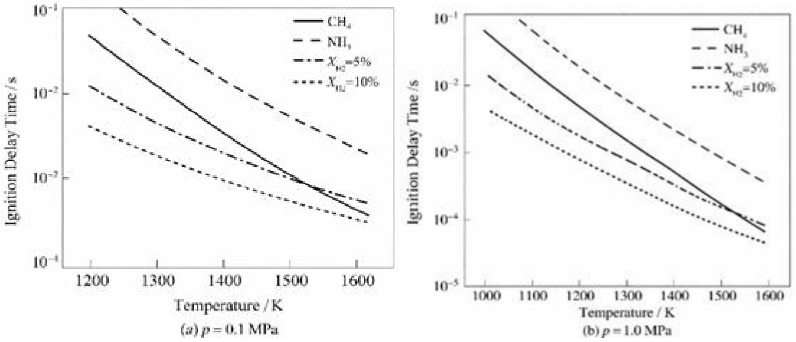

Fig. 1. Ignition delay times for ammonia, ammonia/hydrogen fuel, and methane at different pressures.

4 Combustion chamber technology for flame stabilization and backfire prevention

To address the stability challenges of hydrogen/ammonia fuels, technological development mainly focuses on two goals: "suppressing hydrogen backfire" and "enhancing ammonia flame stabilization". For this purpose, modern technologies mainly adopt measures such as swirl flame stabilization and micro-mixing combustion.

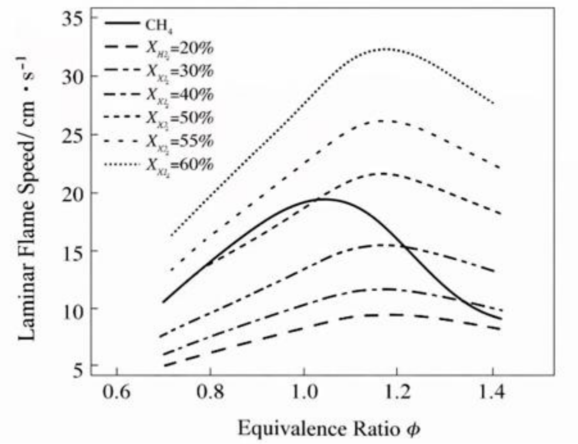

Fig. 2. Laminar flame velocities at different equivalent ratios

4.1 Swirl flame stabilization and enhancement techniques

4.1.1 Basic principles of swirl flame stabilization technology

Swirl flame stabilization is the most classic flame stabilization technique in the combustion chamber of a gas turbine. The basic principle is to organize a strong swirling flow at the head of the combustion chamber to create a high-temperature recirculation zone with a specific aerodynamic structure, thereby providing a stable combustion space and a continuous ignition source for the flame. When faced with the distinct combustion characteristics of ammonia/hydrogen fuels, swirl flame stabilization technology is evolving from a traditional fixed design to an active, adjustable one.

When the premixed ammonia-hydrogen gas passes through the inclined cyclone blades, a large circumferential velocity component is generated. Due to the effect of centrifugal force, the gas flow spreads outward, forming a low-pressure area near the combustion chamber axis, causing the downstream unburned products to flow in the opposite direction to form a central recirculation area. The recirculated high-temperature flue gas continuously heats and ignites the newly injected normal-temperature hydrogen-ammonia gas upstream, ensuring the continuity of the flame. At the same time, there is a shear layer with a large velocity gradient at the edge of the reflux zone, in which the axial velocity of the fresh mixture and the flame propagation velocity can reach equilibrium, thus providing a stable residence position for the flame front. In addition to the central recirculation zone, an outer recirculation zone may form near the combustion chamber wall, and an angular recirculation zone may form at the corner of the cyclone outlet. These complex reflux structures work together to greatly expand the stable boundary of the flame, allowing it to adapt to a wider range of stoichiometric ratios and flow variations.

4.1.2 Swirl flame stabilization technology for ammonia/hydrogen fuel

In response to the high reactivity of hydrogen fuel and the low reactivity of ammonia fuel, more innovative designs have been developed for ammonia/hydrogen fuel swirl flame stabilization technology.

The first and foremost is the high swirl intensity design. Swirl number is a key dimensionless parameter for measuring swirl intensity, defined as the ratio of the angular momentum flux to the axial momentum flux of the gas flow, and is often expressed by the following simplified formula:

$$S = \frac{G_{\emptyset}}{G_x * R} \qquad (1)$$

$$G_{\emptyset} = \int_0^R \rho v v_{\phi} r^2 dr \qquad (2)$$

$$G_x = \int_0^R \rho v^2 r dr \qquad (3)$$

Where R is the radius of the combustion chamber, is the density, is the axial velocity, is the tangential velocity $\rho v v_{\phi}$.

Research shows that increasing the swirl number can effectively expand the size of the reflux zone and enhance the reflux intensity, which is particularly crucial for stabilizing pure ammonia or high ammonia ratio fuels with extremely low flame velocities. For example, Lee et al. from the Korea Institute of Energy Research found in their study of pure ammonia swirl flames that using a strong swirl burner with a swirl number of up to 3.3 can create large-scale, high-intensity reflux zones in the combustion chamber, thereby providing unprecedented stable residence space for pure ammonia flames. It greatly expanded its lean flameout limit and operating range [10]. This strategy of physically "locking" the inert flame through extreme swirl intensity represents a significant breakthrough in ammonia fuel combustion technology.

4.2 Micro-mixing combustion technology

4.2.1 Basic Principles of micro-mixing combustion technology

The principle of micro-mixing combustion is based on a simple fluid mechanics and chemical kinetics inequality, that is, when the residence time of the fuel/air mixture in the premixed channel ($\tau_{residence}$) is greater than the self-ignition delay time of the mixture ($\tau_{ignition}$), backfire is inevitable. The traditional premix combustion chamber has a large premix channel size, and the mixed gas stays in it for a longer time. When the fuel activity is extremely high, the self-ignition delay time is very short, and the above inequality is highly likely to hold, which leads to backfire. To prevent this from happening, the solution for micro-mixing combustion is: Breaking down a single large-scale premixed channel into hundreds or even thousands of sub-millimeter "micro-mixing units" with extremely small characteristic dimensions makes the airflow velocity within the micro-channel more than an order of magnitude higher than that in the traditional channel at the same volumetric flow rate, significantly reducing ($\tau_{residence}$) the time from the entry of the mixture into the channel to its ejection for combustion, typically to the millisecond or even sub-millisecond level. By design, ensure that ($\tau_{residence}$) < ($\tau_{ignition}$) is met across all operating conditions. In this way, the mixture has no time at all to complete the ignition chemical reaction before being ejected from the micro-mixing unit, thus physically eliminating the possibility of backfire.

4.2.2 Micro-mixing techniques for ammonia-hydrogen fuels

Micro-mixing combustion technology is highly adaptable to hydrogen-blended fuels. Because the laminar flame speed of hydrogen can be up to 7-10 times that of natural gas and the ignition delay is extremely short, backfire is highly likely to occur in traditional premixed combustion chambers. Micro-mixing combustion is one of the safest technical paths for high hydrogen blending ratio combustion. The core mechanism is to divide the premix into hundreds of sub-millimeter micro-channels, so that the dwell time of the mixture in the channels is shorter than its self-ignition delay time, thus eliminating backfire from the root. It enables the combustion chamber to operate safely under high hydrogen blending ratio conditions, and both numerical simulations and experimental studies have confirmed its effectiveness. A systematic study by Wang et al. on a certain type of first-generation micro-mixing combustion chamber showed that the combustion chamber remained stable without backfire and the combustion efficiency remained above 99.9% when the hydrogen blending ratio increased from 0% to 60%, demonstrating its reliability and performance advantage in the medium to high hydrogen blending ratio range. Lu Guangpu et al. also noted in their review that micro-mixing burners, due to their anti-backfire properties, have become a key technical solution for companies such as Siemens Energy to achieve 50% hydrogen blending combustion in gas turbines.

5 Combustion strategies for low NOx emissions

5.1 Mechanisms of NOx generation

In the high-temperature environment of ammonia-hydrogen combustion, NOx is generated through two main mechanisms, and hydrogen blending alters the contribution ratio of both.

Fuel-type NOx: This is a major inherent challenge of ammonia combustion, derived from the nitrogen atoms in the fuel molecules. The formation pathway is highly dependent on the local chemical environment, with the core step being the oxidation of the NH amol radical to the intermediate HNO, which in turn generates NO. This pathway is dominant under lean combustion conditions [11].

Thermal NOx: Dominated by the Zeldovich mechanism ($N_2 + O = N + NO$), its formation rate is highly sensitive to temperature. The contribution of thermal NOx is significantly enhanced as the hydrogen blending ratio increases and the combustion temperature rises. It may even become a major source at high hydrogen blending ratios (e.g. >80%).

5.2 Staged combustion technology: two-stage concentration strategy

Staged combustion, especially the two-stage concentration strategy, with its active regulation of the nitrogen chemical reaction path, is currently the most promising low NOx solution for ammonia-hydrogen fuel. The core idea is to create two distinct reaction zones in space [12].

The first level: Rich combustion zone ($\Phi > 1$) This area is anoxic and rich in NH^{+} radicals. The priority of the chemical reaction shifts from "oxidation" to "reduction". The key chain termination reaction $NH_2 + NO = N_2 + H_2O$ becomes the main channel for consuming NO, while NH^{+} radicals can also pass through $NH_2 + NH_2 \rightarrow N_2H_4 \rightarrow \ldots \rightarrow N_2$ and other pathways directly bind to form N_2. The core objective of this stage is to "solidify" as much fuel nitrogen as possible into harmless N_2, cutting off the generation of NOx at its source.

Second stage: Depleted zone ($\Phi < 1$) where secondary air is injected to completely oxidize the unburned fuel (H_2 , NH_3) and its intermediate products that have escaped from the previous stage. Since most of the nitrogen has been removed in the first stage and the second stage itself is in a low-temperature lean combustion state, the formation of both thermal and fuel-type NOx is strongly suppressed.

The numerical simulation of the ammonia-hydrogen premixed swirl flame in the two-stage concentration and dilution combustion chambers by Qu et al. provides the most systematic evidence to date for the effectiveness of this strategy. The study shows that under optimized conditions with a hydrogen blending ratio of 35%, a pressure of 0.5 MPa, and a rich combustion zone equivalent ratio of 1.20, NOx emissions can be as low as 54×10^{-6} (15% O_2), while the combustion efficiency is maintained at approximately 99.9%. This emission level is close to the threshold for commercial application of gas turbines.

6 Conclusion

The paper begins by stating that the polarization of the combustion characteristics of hydrogen and ammonia as zero-carbon energy carriers presents a new impossible triangle of "stable flame - low emission - wide adaptability" for gas turbine combustion chambers. This fundamental contradiction serves as the starting point for the discussion of the entire text. Through systematic review, this paper draws the following core conclusions:

1. The combustion chemistry of ammonia/hydrogen fuel is a fundamental constraint on technological innovation, with an optimal hydrogen blending window of 30% to 50%
2. Swirl flame stabilization provides a stable anchor point for inert ammonia flames through a strong recirculation zone, and a high swirl number (e.g. 3.3) design significantly broadens the stability range of pure ammonia flames
3. Micro-mixing combustion, with its physical anti-backfire mechanism, is the preferred option for high hydrogen blending conditions and can operate safely within the hydrogen blending ratio range of 0-60%
4. Through the spatial decoupling design of rich combustion reduction denitrification and lean combustion exhaust, the two-stage concentration and dilution combustion achieves an order of magnitude reduction in NOx emissions, with NOx emissions as low as 54×10^{-6} under optimized conditions.

The findings reveal that ammonia-hydrogen fuel combustion technology is undergoing a paradigm shift from single-parameter optimization to multi-objective collaborative design. Swirl combustion, micro-mixing combustion, staged combustion - the three technologies, each performing its own role and complementing each other, together form the scientific basis of the zero-carbon gas turbine combustion chamber. The findings of this study are of great reference value for gas turbine combustion chamber designers, zero-carbon fuel policymakers, and researchers engaged in the integration of ammonia-hydrogen energy systems. The structural modification of the co-combustion chamber and the conditional ratio of ammonia/hydrogen fuel are realistic choices for engineering applications at the current technological level and the inevitable path towards green and low-carbon.

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