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Experimental Investigation of the Combustion Characteristics of Ammonia Addition to the Dry Low NOx Hydrogen Combustor

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ABSTRACT

To facilitate the decarbonization of the energy sector and promote the market penetration of hydrogen, exploring the feasibility of using ammonia as an energy carrier in existing combustion equipment becomes an important topic. Partial cracking or mixing with other fuels is currently the common strategy to improve ammonia's slow chemistry and low reactivity.

We conducted an experimental study of ammonia addition to an existing low-pollution hydrogen gas turbine combustor, observing flame structure changes, measuring NOx emissions, and investigating flashback boundaries. The results show that after adding only 5% ammonia, the flame structure changed significantly, and the flame expansion angle became more extensive, but it did not affect the flame stability and working condition regulation. Also, no ammonia escape occurs. Meanwhile, the addition of ammonia expanded the flashback boundary to some extent. However, the main issue facing the addition of ammonia is the significant increase in NOx emissions. The practice of this paper provides a reference for the feasibility of adding ammonia gas to the low-pollution hydrogen gas turbine combustor.

Keywords: Hydrogen-ammonia mixed combustion, lean premix combustor, combustion characteristics, NOx emissions

NONMENCLATURE

Abbreviations	
DLN	Dry Low NOx
CRN	Chemical Reaction Net

1. INTRODUCTION

The decarbonization of the prime movers in the industrial power generation and energy sectors appears to be essential to fulfill the environmental obligations concerning GHG emissions[1]. In the process of energy transformation, the intermittency of renewable energy, such as solar, wind, and tidal, becomes an important obstacle. Among the different energy storage approaches, the chemical energy stored in energy-dense fuels appears particularly efficient and suitable[2], among which hydrogen is an ideal alternative. Hydrogen can be produced via renewable energy resources through water electrolysis [3]. Despite hydrogen's advantages, its storage, distribution, and infrastructure challenges remain[4]. Based on the above, ammonia as an energy vector is gaining more interest for future power generation, transportation, and heating systems[5]. However, compared to conventional hydrocarbon fuels, ammonia's low reactivity characteristics and higher NOx emissions limit its practical application.

Many scholars discussed ammonia utilization for power and heat generation. The review article by Kobayashi et al.[4] summarizes the ammonia combustion studies on lab-scale and actual practical combustors. The results indicate that when a gas turbine combustor fueled by pure ammonia, ammonia-methane[6], ammonia-hydrogen, or ammonia-kerosene, a selective catalytic reduction (SCR) system had to be installed downstream of the turbine to achieve acceptable NOx emissions below ten ppm[6]7][8][9]. For this reason, two-stage combustion, also referred to as rich-quench-lean (RQL), has been proposed as a suitable technology for gas turbine combustors fueled by

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ammonia and its blends. Many efforts were made to optimize two-stage combustors by selecting the fuel ratio of the primary rich stage or the global equivalence ratio[10][11][12][13]. Kobayashi [4] and Ayman M. Elbaz[5] listed several numerical and experimental studies showing the potential of two-stage combustion for NO reduction. Multiple studies also note that the dilemma of choosing between low NOx and low NH3 emissions is often made when developing ammonia classification strategies. In conclusion, the application of ammonia in gas turbines is still in the exploratory stage.

Most of the previous studies have been aimed at improving the low reactivity of ammonia by adding small amounts of methane or hydrogen to existing hydrocarbon combustion facilities. But less research has been done to inject small amounts of ammonia into existing dry low NOx (DLN) hydrogen combustion chambers, and quantitative analysis of combustion performance is not yet fully understood.

This paper aims to give the most recent experimental results in ammonia addition to the DLN hydrogen combustion chamber under elevated pressure conditions, including the flame structure, NOx emissions, and flashback boundaries. The primary purpose is to evaluate the feasibility of the technical route of hydrogen-blend ammonia combustion based on the existing DLN hydrogen gas turbine and provide the route reference for the efficient and clean utilization of ammonia in gas turbines.

2. EXPERIMENTAL APPARATUS AND MEASUREMENT

2.1 Hydrogen DLN combustor description

Figure 1 shows a schematic diagram of the structure of a hydrogen dry low NOx combustor, which is based on the concept of the lean premix and axial radial mixed classification. The focus of this paper is on the combustion performance of the head nozzle in the design condition, as shown in the red rectangle in Fig. 1. The nozzle is designed based on the concept of center stage design, which has taken measures to inhibit the flashback of hydrogen. The flow path is divided into three concentric arrangements: pilot stage, partially premixed stage, and main combustion stage. Among them, the pilot stage adopts the diffusion combustion mode mainly plays the role of ignition and watch; The partially premixed set uses the two-stage air swirl structure to strengthen the mixing with hydrogen to form partially premixed combustion. The array standing-vortex flow enhances the primary combustion stage's hydrogen and air mixture structure to develop homogeneous premixed gas and construct a lean premixed flame. The following measures were taken to suppress the flashback problem caused by hydrogen: (1) The primary combustion stage was built into a cone shape for a higher velocity at the outlet. (2) Cooling holes are arranged at the end of the outer wall of the primary combustion casing to increase the flow velocity at the wall boundary layer and reduce the equivalent ratio. (3) Arrange cleaning slots on the suction surface of the vortex blade to inhibit the generation of secondary vortices.

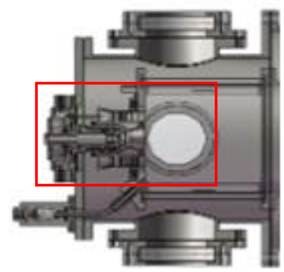


Fig. 1. Schematic diagram of hydrogen combustor

2.2 Experimental apparatus and measuring method

Figure 2 shows the experimental apparatus setup and measurement equipment arrangement. The compressor assembly supplies air and flows counter-currently along the combustion chamber annulus into the head nozzle. The fuel is supplied from the gas cylinder assembly and fed to each nozzle stage. For the ammonia addition test, ammonia and hydrogen are mixed after each completed the measurement and fed into the main combustion stage for combustion. The flue gas, after combustion, is combined with the air at the dilution holes of the combustor and then discharged at an acceptable exhaust temperature.

The primary measuring system is listed as follows. The mass flow controller measures the fuel mass flow, while air is measured by the pitot tube. SONY CCD cameras monitored the flame, and the heat release in the combustion zone was monitored by OH distribution using the UV camera. The UV camera details are listed below: Lucid ATX204S-MC with 4504X4504 pixels, the frame count is 200fps, the lens adopts a standard UV prime lens with a focal length of 25 mm; while adding a 310 nm filter. CCD camera and UV camera work together to judge the flame structure and the variation of heat release zone.

NOx emissions were measured by Testo 350 flue gas analyzer, while another large-range NOx measurement device was also connected. Two flue gas analyzers with different ranges work together to ensure that the NOx values measured in this paper are reliable.

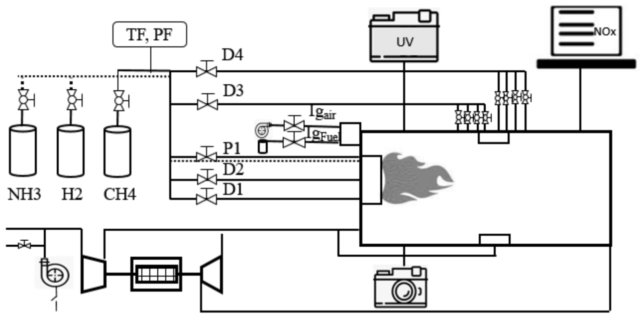


Fig. 2. Schematic of experiment arrangement and measurement

2.3 Experimental conditions

According to practice, this paper mainly discusses the ammonia addition range of 0-5% to explore the effects of adding a small amount of ammonia. The experimental conditions are shown in Table 1.

Table 1 Experimental conditions

Description (units)	Value
Nozzle type	Swirl
Equivalence ratio	0.28-0.3
Inlet pressure (MPa)	0.36
Inlet temperature (K)	463
Heat power(kW)	230

3. THEORY CALCULATION

Table 2 shows the combustion properties of H_2, NH_3, and H2-NH3 blended fuels. As shown, the heating value and the maximum laminar burning velocity(1atm,298K) of ammonia-air fame are far lower than hydrogen. The calculation results show that the mass calorific value decreases significantly after adding 5% ammonia, and the laminar flame propagation speed decreases significantly.

Table 2 Combustion properties of H2, NH3, and blend fuels

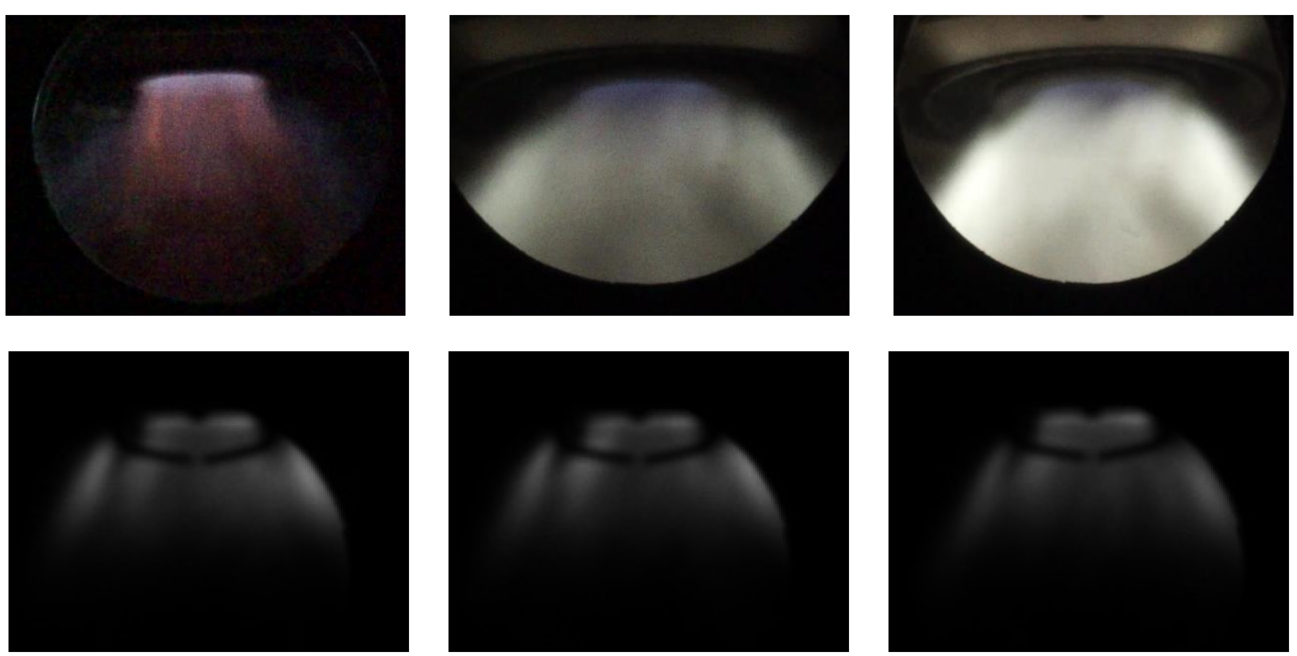
Fuel	H_2	NH_3	5%NH_3 -H_2
Lower calorific value (MJ/kg)	120	18.6	87.75
Burning velocity (cm/s)	291	7	156
Flame temperature (K)	2383	2073	2230

4. RESULTS

4.1 Flame structure

During the whole test process of adding ammonia, the combustion chamber combustion status remained stable without flame instability as the amount of ammonia added gradually increased to 5% from 0%. In this paper, three typical working conditions are given for detailed analysis.

Figure 3（top） shows that with the increase of ammonia gas, the flame angle becomes significantly more extensive, and the color of the flame gradually changes from blue and purple in pure hydrogen combustion to white and then yellow, showing the characteristics of ammonia gas flame. Notably, the flame



(a).pure hydrogen (b).3% ammonia (c). 5% ammonia

Fig.3.Flame structure and OH distributions in the combustor

root of the primary combustion stage of the combustion chamber still showed a blue-purple color after adding ammonia, indicating the phenomenon of hydrogen-ammonia layered combustion due to the high flame propagation speed of hydrogen gas.

Figure 3（bottom） shows the OH distribution, which can reflect the variation of the flame heat release zone. It can be seen that with the increase of ammonia gas, the area of the flame exothermic zone has no noticeable change, but the intensity of flame heat release is weakened.

4.2 NOx emissions

As shown in Figure 4, NOX surged after 3% ammonia was added, and NO increased more than NO2 under the conditions of 0.36MPa and 463K. The two operating conditions show the same NOx emission gauge trend changes.

It should also be noted that after theoretical calculations, the combustion chamber outlet temperature values based on fuel consumption matched the measured values, indicating no ammonia escape occurred.

In summary, adding a small amount of ammonia to the lean premixed hydrogen low-pollution combustor significantly increased the NOx emissions, but no ammonia escape occurred. This experimental result indicates that NOx emissions should be focused on, especially in the subsequent improvements. However, special attention must be paid to the low NOx and NH3 emissions balance.

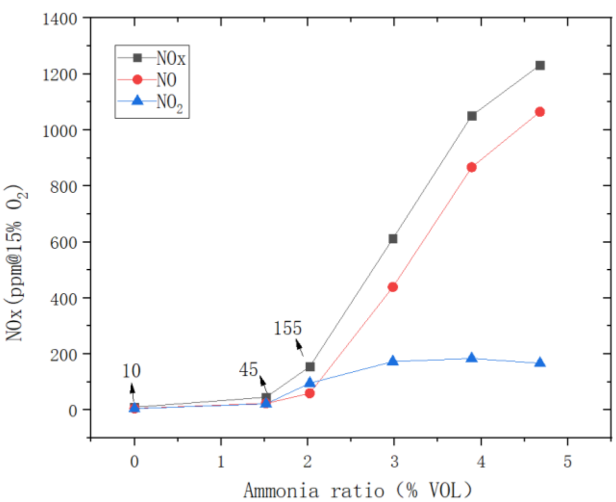
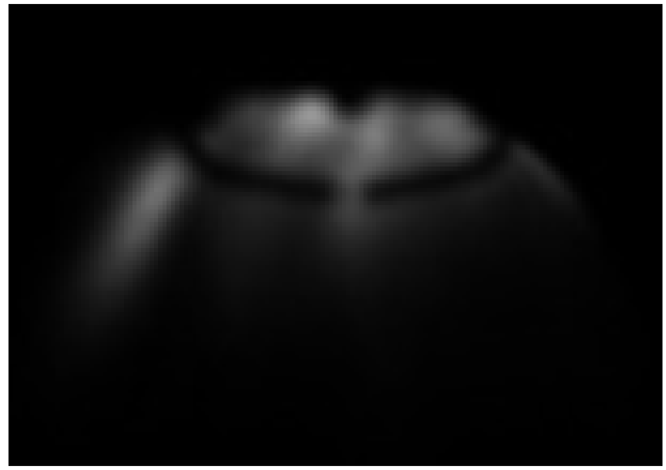


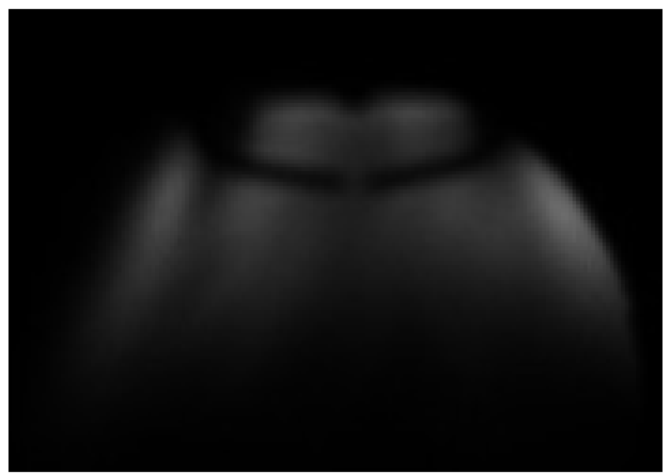
Fig.4. NOx emissions under different operating conditions

4.3 Flashback boundary

Figure 5 shows the comparative effect of adding ammonia to suppress the combustor's flashback under overload conditions effectively. Figure 5(a) shows the flame state during the flashback of the hydrogen combustor. Figure 5(b) shows the stable combustion state after adding 2% ammonia at the same exothermic power. The comparison results show that adding a small amount of ammonia can suppress the flashback of the hydrogen combustor to some extent and broaden the operating range of the gas turbine. The reasons for ammonia inhibition of flashback will be analyzed in the 5.2 discussion section.



(a). Flame structure during a flashback of pure hydrogen



(b). Stable combustion after adding 2% ammonia

Fig.5. Inhibition of flashback by the addition of ammonia

5. DISCUSSION

The above experiment results show that the addition of 5% ammonia to a DLN hydrogen combustor designed based on a lean premix concept results in a stable combustor with no ammonia escape and facilitates the suppression of flashback, which is exciting for the use of ammonia fuels at existing facilities. However, the spike in NOx needs attention, indicating that the ammonia decomposition route needs to be combined with an ultra-high cracking degree ammonia decomposition degree unit or with an SCR plant downstream. The ammonia decomposition degree should preferably exceed 99%. This paper presents the following analysis of the reasons for the changes in flame structure, flashback boundary, and NOx after adding ammonia.

5.1 Variation of laminar flame propagation speed and its effect

The unstretched laminar burning velocity(S_L)is considered one of the most crucial properties controlling combustion behavior. It is used in this paper to analyze why the flame structure and flashback boundaries change after the addition of ammonia in premixed flames of the combustor.

The mei mechanism[14] was applied to calculate the laminar flame speed at different ammonia ratios under the design conditions shown in Table 1, and the calculated results are shown in Figure 6. It can be seen that as the volume fraction of ammonia gradually increases, the laminar flame propagation speed of the mixed fuel decreases significantly, and the flame propagation slows down while causing the flame to propagate radially, which is the main reason for the change in flame tension angle. At the same time, due to the slowdown of flame propagation, the flashback phenomenon is also suppressed. In addition, it can also be seen in Figure 6 that the laminar flame propagation velocity of the gas mixture decreases more drastically with the addition of ammonia as the equivalence ratio increases.

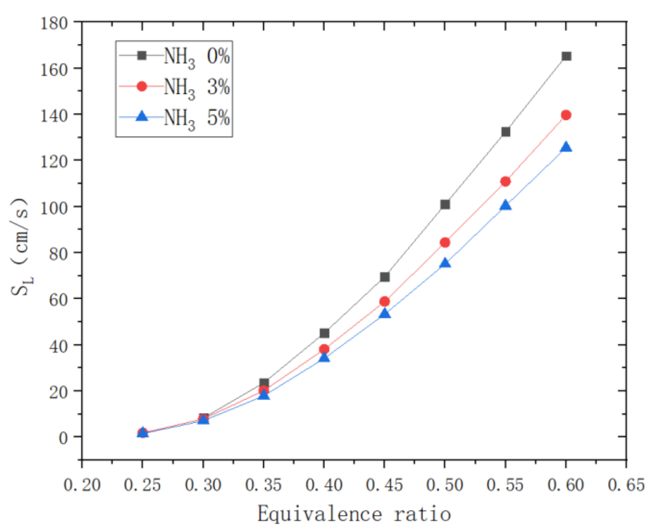


Fig.6. The variation pattern of laminar flame propagation speed with the proportion of ammonia

5.2 Effect of hydrogen-ammonia mixed combustion chemistry on NOx generation

The relationship between different ammonia additions and NOx emissions was studied using the CRN model, and Figure 7 shows the sensitivity analysis and the main chemical reaction pathways. The sensitivity factor was defined as the ratio of the percentage change in NOx to the percentage change in ammonia.

As shown in Figure 7, the sensitivity coefficient is highest at the initial addition of minimal amounts of ammonia and then becomes progressively smaller before leveling off. As the amount of ammonia added gradually increased from 1% to 10%, the sensitivity coefficient did not change significantly. This result indicates that the surge of NOx is mainly due to the change of the main pathway of NOx generation from thermal NOx in the case of pure hydrogen to the dominance of fuel-based NOx. This conclusion is supported by the analysis of the chemical reaction pathways shown in Figure 7.

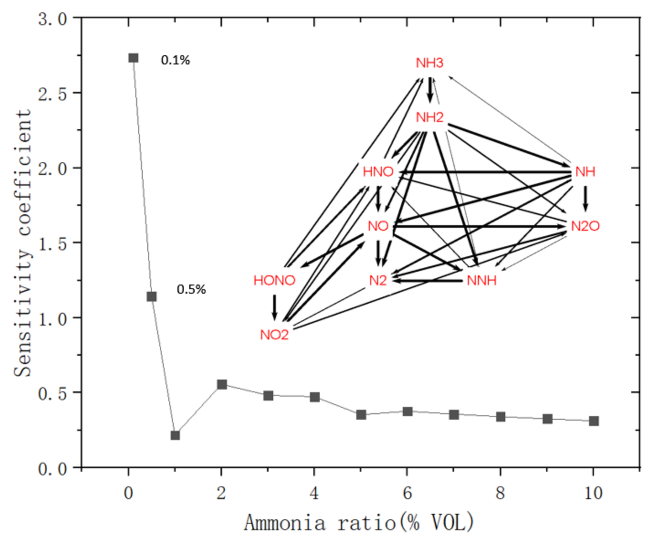


Fig.7. Sensitivity and Mechanism analysis of NOx

6. CONCLUSIONS

Exploring the feasibility of carbon-free fuel ammonia in Dry Low NOx combustors of the existing gas turbines is of great practical importance to solving the carbon emission problem.

We conducted an experimental study of ammonia addition to an existing DLN hydrogen gas turbine combustor, observing flame structure changes, measuring NOx emissions, and investigating flashback boundaries. The obtained experimental results are also discussed and analyzed.

The results of the experiment show that, with the increase of ammonia, the flame angle becomes significantly more prominent, and the color of the flame gradually changes from blue and purple in pure hydrogen combustion to white and then yellow, showing the characteristics of ammonia gas flame, also the flame heat release region has no noticeable change. However, the intensity of flame heat release is weakened.

The comparison results show that adding a small amount of ammonia can suppress the flashback of the hydrogen combustor to some extent and broaden the operating range of the gas turbine. However, adding a small amount of ammonia resulted in a significant increase in NOx emissions.

This paper reveals that adding 5% ammonia to the hydrogen combustor does not affect flame stability and combustion efficiency and even facilitates widening the flashback boundary. However, there is a phenomenon of NOx spike. Therefore, the NOx reduction is the main challenge of using ammonia in practical DLN hydrogen combustion devices relying on lean premixed burning as a NOx abatement mechanism. The test results also show that ammonia utilization using ammonia decomposition on a combustion unit based on a lean combustion concept needs to be combined with an ultra-high cracking degree ammonia cracker or with a downstream SCR unit. Therefore, an optimized fuel classification strategy should be provided to balance the NOx emission and ammonia escape problems in the future.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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