NO and OH* emission characteristics of very-lean to stoichiometric ammonia-hydrogen-air swirl flames

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Abstract

One of the main concerns regarding ammonia combustion is its tendency to yield high nitric oxide (NO) emissions. Burning ammonia under slightly rich conditions reduces the NO mole fraction to a low level, but the penalties are poor combustion efficiency and unburnt ammonia. As an alternative solution, this paper reports the experimental investigation of premixed swirl flames fueled with ammonia-hydrogen mixtures under very-lean to stoichiometric conditions. A gas analyzer was used to measure the NO mole fraction in the flame and post flame regions, and it was found that low NO emissions (as low as 100 ppm) in the exhaust were achieved under very lean conditions ($\phi \approx 0.40$). Low NO emission was also possible at higher equivalence ratios, e.g. $\phi = 0.65$, for very large ammonia fuel fractions ($X_{NH3} > 0.90$). 1-D flame simulations were performed to elaborate on experimental findings and clarify the observations of the chemical kinetics. In addition, images of OH* chemiluminescence intensity were captured to identify the flame structure. It was found that, for some conditions, the OH* chemiluminescence intensity can be used as a proxy for the NO mole fraction. A monotonic relationship was discovered between OH* chemiluminescence intensities and NO mole fraction for a wide range of ammonia-hydrogen blends ($0.40 < \phi < 0.90$ and $0.25 < X_{NH3} < 0.90$), making it possible to use the low-cost OH* chemiluminescence technique to qualify NO emission of flames fueled with hydrogen-enriched ammonia blends.

Keywords: carbon-free; ammonia; swirl flame; NO emission; OH* chemiluminescence

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1. Introduction

Because of its carbon free nature, ammonia (NH$_3$) and its blends (NH$_3$-H$_2$, NH$_3$-natural gas, etc.) are promising fuels for future power generation. Ammonia has a relatively high volumetric energy density and its use in the fertilizer industry means that the technology for its production, transport and storage are readily available. The two main challenges typically associated with the use of ammonia for power generation are: (1) it is weakly reactive compared to hydrogen and natural gas, causing a relatively low flame speed and reduced flammability limits [1, 2] and (2) it is prone to generating high NO emissions [3, 4].

The stable operation of flames fueled by ammonia blends has been demonstrated in many configurations, including atmospheric and pressurized model gas turbine combustors [1] and an industrial micro gas turbine [5]. Among all operating conditions investigated, a small subset of conditions was shown to yield low NO emissions [6]. This was attributed to the prevalence of fuel NOx pathways [7, 8], which differ from thermal NOx pathways that are typically encountered in hydrocarbon and hydrogen flames [7]. In particular, burning fuel blends with a large volume fraction of ammonia in a premixed mode, and at slightly rich equivalence ratios (1.05 $\leq \phi \leq$ 1.20), led to substantially decreased NO emissions, compared to stoichiometric or slightly lean mixtures [3, 9, 10]. However, rich burning implies that a second combustion stage must be used to avoid efficiency issues and unburnt ammonia emissions. Successful operation of a staged combustor fueled with ammonia was shown in [11].

Using hydrogen-ammonia blends, Valera-Medina et al. [12] and Khateeb et al. [13] demonstrated that it is possible to stabilize very lean ($\phi \leq$ 0.50) flames in model gas turbine combustors. However, a minimum of about 20% hydrogen by volume in the fuel blend seems to be required. Valera-Medina et al. [12] also proved that these very lean conditions yielded more than an order magnitude decrease of NO mole fraction compared to slightly lean and stoichiometric conditions.
With the 50:50 by vol. H₂-NH₃ blend investigated at 10 bar, the NO mole fraction in the flame products at $\phi = 0.30$ was comparable to that at $\phi = 1.10$, which is a low 100 ppm. However, the best reported global performance remains at a rich equivalence ratio of $\phi = 1.20$ with around 30 ppm.

Because only one 50:50 by vol. H₂-NH₃ blend was investigated in [12], it is not clear whether better NO emission performances could be achieved for very lean flames if the H₂-NH₃ blend was optimized. It is the objective of this study to clarify this point.

The model gas turbine combustor used by Khateeb et al. [13] allowed stabilizing swirl flames for a wide range of lean-to-rich equivalence ratios and hydrogen enrichments in ammonia. For this reason, it was used in this study. Global and local NO mole fractions were measured over a range of operating conditions to identify suitable very-lean or lean operating conditions for the stable and clean operation of gas turbine combustors fueled by H₂-NH₃ blends. To relate global NO emission performance to the flame structure, time-averaged, but spatially resolved images of OH* chemiluminescence—as well as local NO mole fractions—were also recorded. It was shown that relatively cheap and easy chemiluminescence experiments could be surrogates for local NO mole fraction measurements for many of the lean H₂-NH₃-air flames of interest here. The analysis of NO and OH* emission characteristics was aided by 1-D freely-propagating-flame simulations featuring detailed chemistry.

2. Experimental setup and methods

Experiments were conducted in an atmospheric laboratory-scale swirl combustor; its main features are shown in Fig. 1a. It is identical to that used in [13] and similar to that in [14]. A fraction of the combustion air was injected axially, the remaining air mixed with fuel and then injected tangentially, 140 mm upstream of the combustion chamber entrance. The swirl number produced by this injection
strategy could be varied but was kept equal to $S_w = 1$ for all conditions examined here; it was calculated following the definition of [15]. The swirled mixture of reactants entered the combustion chamber through a pipe of $D = 40\text{mm}$ diameter at 293 K. The bulk Reynolds number, based on the pipe diameter and the bulk injection velocity, was fixed to $Re = 5,000$. This combustor was technically premixed and, using non-reactive RANS simulations, it was verified that the mixture inhomogeneities at the injection plane was smaller than 3.5 %.

Figure 1: (a) Schematic of swirl burner and (b) sampling probe.
To mitigate the effects of heat-loss, the 152-mm diameter cylindrical combustion chamber had ceramic walls. To provide optical access, three 50 mm wide UV fused-silica windows were mounted on one side and stitched together to mimic the curvature of the ceramic walls. This did not introduce significant flame asymmetries. A converging section was also mounted on top of the combustion chamber to accelerate combustion products and prevent the entrance of ambient air.

Different blends of ammonia and hydrogen were investigated with ammonia volume fractions in the fuel blend ranging from $X_{\text{NH}_3} = 0.50$ (50:50 $\text{H}_2$-$\text{NH}_3$) to 1.00 (pure ammonia). Lean to stoichiometric equivalence ratios were investigated, $0.40 \leq \phi \leq 1.05$. Mass flow rates were prescribed using thermal mass flow controllers (MKS Instruments) with an accuracy better than 2 %, causing imprecision in the Reynolds number, ammonia fuel fraction, and equivalence ratios of maximum 5 %.

The mole fraction of NO was measured at different locations in the combustion chamber using a Horiba VA-3022 dual CLD analyser connected to a Horiba VS-E-3005 sampling conditioning unit. Samples were collected through a quartz probe (dimensions in Fig. 1b). Its design was similar to that used in [16], with a small inlet diameter of 1 mm providing sonic conditions at the nozzle, and quenching chemical reactions. The cross-sectional area of the sampling probe was very small (~0.03%) compared to that of the combustion chamber. Visual inspection of the flame with and without probe confirmed that perturbations were not significant. Tests conducted at different radial locations of the homogeneous exhaust showed no variations, suggesting that inclusion of ~40 mm length of probe within hot products did not promote continued reactions within the probe. The pipe connecting the probe to the analyser was heated to 425 K to avoid water condensation; sensitivity of the NO mole fraction measurements was around 1 ppm, and the accuracy and precision were approximately 5 % and 4 %, respectively.
Global NO emissions were measured by positioning the probe at location $P_0$ (see Fig. 1a) in the homogeneously mixed exhaust gases, 455 mm away from the injection plane. Local NO mole fractions were also measured at different locations inside the combustion chamber. Three heights were investigated by passing the probe through the ceramic side wall at positions $P_1$, $P_2$, and $P_3$, corresponding to heights $z = 20$, 60, and 140 mm ($z/D = 0.5$, 1.4, and 3.5), respectively. The probe was also translated horizontally to measure the NO mole fraction at different radial locations.

Images of OH* chemiluminescence were recorded using an ICCD camera (Princeton Instruments, PI-Max4) operated at a frame rate of 10 Hz. It was fitted with a UV lens ($f = 100$ mm, $f/2.8$) and a 10-nm band-pass filter, centered around 310 nm (Asahi Spectra ZBPA310). The intensifier gate duration was set to 10 ms and time-average OH* chemiluminescence images were obtained by averaging more than 600 images. An Abel deconvolution [17] was then performed to infer the spatial distribution of time-average OH* chemiluminescence intensity in the central longitudinal plane.

To guide the analysis of the measured NO and OH* emission characteristics, 1-D simulations of freely-propagating-flames (FPF) were conducted with Chemkin-Pro [18] and the chemistry mechanism by Mathieu and Petersen [19]. This mechanism has been well validated for ammonia-hydrogen flames and includes sub-mechanisms for both NO and OH* [12, 20, 21].

3. Results and Discussion

3.1 Exhaust NO mole fraction

Figure 2 shows the NO mole fraction measured in the homogeneous-mixed exhaust gases (position $P_0$) for different ammonia fuel fractions and equivalence ratios. It ranged from around 100 ppm for $X_{NH_3} = 0.50$ and $\phi = 0.40$ to 4,900 ppm for $X_{NH_3} = 0.80$ and $\phi = 0.85$ (note that the range of ammonia
fuel fraction and equivalence ratio investigated were restricted by the stability limits of this burner [13]).

![Figure 2: Measured NO mole fraction in exhaust gases as a function of ammonia fuel fraction for different equivalence ratios.](image)

The following trends of NO mole fraction were observed from Fig. 2:

- For $0.65 \leq \phi \leq 1.00$, the NO mole fraction decreased continuously with the ammonia fuel fraction.
- For a fixed ammonia fuel fraction, the NO mole fraction was not a continuous function of equivalence ratio. The NO mole fraction took its minimum value for $\phi = 0.40$; it then increased with the equivalence ratio until $\phi = 0.85$. However, it decreased with equivalence ratio between $\phi = 0.85$ and $\phi = 1.00$. This non-monotonic trend was comparable with that observed in [22] for pure ammonia. However, the NO mole fractions measured here were smaller than those reported in [22].
- For a very lean equivalence ratio of $\phi = 0.40$, NO mole fractions were relatively low--less than 250 ppm--across the entire range of stable ammonia fuel fractions. Minimal NO mole fractions (equal to or smaller than the analyzer sensitivity of 100 ppm) were found for the two extreme ammonia fuel fractions $X_{\text{NH}_3} = 0.50$ and $X_{\text{NH}_3} = 0.80$. 
To allow fair comparisons across equivalence ratios, it is useful to correct NO mole fractions for dilution. Following the correction procedure described by [23], it is found that 15% O₂-corrected NO mole fractions for φ = 0.4 remain below 100 ppm for X_{NH₃} = 0.5 and 0.8 and below 140 ppm for X_{NH₃} = 0.6 and 0.7.

These data corroborate and extend the findings in [12], that good NO emission performance can be achieved for very lean equivalence ratios and hydrogen-enriched ammonia flames.

To consider gas turbines operating with very lean hydrogen-enriched ammonia flames, N₂O emission should be examined as it has a global warming potential around 250 times larger than CO₂. To illustrate, any hydrogen-enriched ammonia flame exhausting flue gases with around 240 ppm of N₂O, but no CO₂, would have roughly the same global warming impact than the CO₂ emitted by a methane-air flame with an equivalence ratio of φ = 0.60. A N₂O mole fraction of 240 ppm is only twice that measured by [11] in a 30:70 (by vol.) ammonia-methane flame with an equivalence ratio of φ = 0.60. The mole fraction of N₂O was not measured in the present study. However, 1-D FPF simulations conducted with Chemkin and the chemistry mechanism from [19] suggest that the N₂O mole fraction in the post-flame region does not exceed 30 ppm in ammonia-hydrogen-air flames with φ = 0.50 and X_{NH₃} ≤ 0.60. Simulations did not converge for equivalence ratios below φ = 0.50 or for X_{NH₃} > 0.60. Regardless, this warrants further study.

Figure 3a-b shows the calculated NO mole fraction (solid red lines) in the burnt product of 1-D flames as a function of ammonia fuel fraction (a) or equivalence ratio (b). Because of flame stabilization issues, 1-D FPF simulations could not be converged for φ < 0.50 and X_{NH₃} > 0.60. Flashback prohibited the stabilization of swirl flames for φ > 0.50 and X_{NH₃} ≤ 0.60, therefore, there was no overlap between measured and calculated conditions for the very lean hydrogen-enriched ammonia flames of interest here, however, trends can be compared.
In the 1-D FPF simulations, the NO mole fraction has been extracted 5 cm downstream of the flame front. Note that, because thermal NOx pathways do not play a large role in NO formation in the flames examined here, the NO mole fraction does not change significantly downstream of the flame front in most cases.

In Fig. 3a, the calculated NO mole fraction is a non-monotonic function of ammonia fuel fraction for $\phi = 0.50$ and $\phi = 0.65$. The NO mole fraction initially increased when the ammonia fuel fraction increased and it peaked around $X_{\text{NH}_3} = 0.20$ and $X_{\text{NH}_3} = 0.25$ for $\phi = 0.50$ and $\phi = 0.65$, respectively. The NO mole fraction then decreased when the ammonia fuel fraction increased at a fixed equivalence ratio. This was the same trend observed experimentally for $\phi = 0.65$ and $X_{\text{NH}_3} > 0.70$ in Fig. 2. Both Figs. 2 and 3 show that, if $\phi < 0.90$, decreasing the equivalence ratio at a fixed ammonia fuel fraction causes decreased NO mole fraction. Results from the simulations and experiments both showed that burning hydrogen-enriched ammonia flames at a very lean equivalence ratio is a promising strategy to abate NO emissions. However, there was a trade-off: If the ammonia fuel fraction was larger than approximately 20-25 % by volume, it was advisable to further increase the ammonia fuel fraction. However, increasing the ammonia fuel fraction (equivalent to reducing the hydrogen fuel fraction) above a critical value, function of equivalence ratio, led to blow-out. Based on the measurements in Fig. 2, for good NO emission performances, the ammonia fuel fraction should be greater than $X_{\text{NH}_3} = 0.50$ for $\phi = 0.40$. It should be larger than $X_{\text{NH}_3} = 0.90$ for $\phi = 0.65$. However, for $\phi = 0.40$ and $\phi = 0.65$, blow-out occurs for $X_{\text{NH}_3} = 0.80$ and $X_{\text{NH}_3} = 0.95$, respectively [13].

Excepting mixtures with a marginal amount of ammonia, no ammonia fraction yields good NO emission performances for $\phi = 0.85$. Good performances were recovered for stoichiometric and
slightly rich equivalence ratios for very large ammonia fuel fractions $X_{\text{NH}_3} > 0.90$—which was also observed by others [4, 24]; it is also shown in Fig. 3b.

Pathways for the formation of NO differ in ammonia and hydrogen flames; these have been previously studied [7, 8], and it was shown that higher OH radical mole fractions increased NO formation for fuel blends with a large fraction of ammonia. This explains why reducing the equivalence ratio at a fixed ammonia fuel fraction handicaps NO formation. The high reactivity of hydrogen produces larger quantities of OH compared to that produced with ammonia, this also explains why decreasing the ammonia fuel fraction at a fixed equivalence ratio promotes NO formation.

Figure 3: (a) Computed NO (red) and OH* (black) mole fraction as a function of ammonia fuel fraction for $\phi = 0.50$ and 0.65. (b) Same as (a), but as a function of equivalence ratio for $X_{\text{NH}_3} = 0.80$ and 0.90.
3.2. OH* chemiluminescence intensity as a surrogate for NO mole fraction

N₂O, OH, H, and O radicals contribute to the NOx chemistry in ammonia flames through fuel NOx pathways [7, 8]. These radicals are also known to influence the formation of OH* radicals in ammonia-hydrogen flames [19]. For this reason, some correlation between the local NO mole fraction and the OH* chemiluminescence intensity is expected. If confirmed, this property of ammonia-hydrogen flames could be used to develop cheap, non-intrusive methods for examining local NO mole fractions in flames.

Figure 3 also shows the OH* chemiluminescence intensity (black solid lines) computed in 1-D flames as a function of ammonia fuel fraction (a) or equivalence ratio (b). If the ammonia fuel fraction was large enough (\(X_{\text{NH}3} \geq 0.25\)), for very lean equivalence ratios \(\phi = 0.50\) and \(\phi = 0.65\) (Fig. 3a), the OH* chemiluminescence intensity and NO mole fraction both decreased when the ammonia fuel fraction increased. When the equivalence ratio was small enough (\(\phi < 0.90\)), for very large ammonia fuel fractions \(X_{\text{NH}3} \geq 0.80\) (Fig. 3b), the OH* chemiluminescence intensity and NO mole fraction both increased with increased equivalence ratio. This confirms that there is a monotonic relationship between OH* chemiluminescence intensity and NO mole fraction over a large range of lean hydrogen-enriched ammonia flames (note that the range of equivalence ratio and ammonia fuel fraction over which this monotonic relationship holds includes ranges where NO emission performances were good).

The relationship between OH* chemiluminescence intensity and NO mole fraction was further examined in the swirl flames. Figure 4 shows time-average Abel-deconvoluted images of OH* chemiluminescence images for a subset of the operating conditions described in Fig. 2. These images were normalized with respect to the most intense pixel in the most intense flame (\(X_{\text{NH}3} = 0.90\) and
\( \phi = 1.00 \). The OH* chemiluminescence intensities can be compared quantitatively across all pixels in one image and across operating conditions.

Figure 4 shows that all the flames featured a similar V shape, but different sizes. More importantly, this figure shows that the ammonia fuel fraction and equivalence ratio greatly influenced OH* chemiluminescence intensity. For \( \phi = 0.40 \) and \( \phi = 0.65 \), decreasing the ammonia fuel fraction increased the OH* chemiluminescence intensity. For \( X_{\text{NH3}} = 0.70 \), increasing the equivalence ratio from \( \phi = 0.40 \) to \( \phi = 0.65 \) increased the OH* chemiluminescence intensity. These trends were also observed in the 1-D FPF simulations described in Fig. 3.

![Figure 4: Time-average Abel-deconvoluted images of OH* chemiluminescence for nine flames featuring different ammonia fuel fractions and equivalence ratio. White circles represent some locations where NO mole fractions were measured (unit for distance: mm).](image)

To examine the relationship between local OH* chemiluminescence and local NO mole fraction, the local NO mole fraction was measured at different locations in the central longitudinal plane. Results are shown in Fig. 5 for three heights above the burner (heights \( P_1 \), \( P_2 \), and \( P_3 \) in Fig. 1) and eight evenly distributed radii from \( r = 0 \) to 70 mm, leading to 24 locations per flame. To facilitate the analysis, some of these locations are highlighted in the central image of Fig. 4. A subset of six flames from those shown in Fig. 2 was selected.
Figure 5: Radial profiles of NO mole fraction measured at three different heights, \( z = 20 \) (red), 60 (blue), and 140 mm (black), in six different flames.

At height \( P_1 \) (\( z/D = 0.5 \) and \( z = 20 \) mm), and across all flame conditions, the local NO mole fraction took its maximum value inside the inner recirculation zone. The peak NO mole fraction varied from 200 ppm for \( X_{\text{NH}_3} = 0.70 \) and \( \phi = 0.40 \) to 5600 ppm for \( X_{\text{NH}_3} = 0.90 \) and \( \phi = 0.85 \). Overall, the peak local NO mole fraction measured at height \( P_1 \) was larger than the global NO mole fraction measured at \( P_0 \). This was an expected feature, emphasized by the radial profiles measured at heights \( P_2 \) and \( P_3 \). \( P_2 \) was located immediately downstream of the tallest flame at \( z = 60 \) mm (\( X_{\text{NH}_3} = 0.90 \) and \( \phi = 1.00 \)). Therefore, no reaction layer was crossed, and the radial profile of NO mole fraction was flatter and took smaller values. At height \( P_3 \) (\( z = 140 \) mm), burnt products were almost homogeneously mixed (except in the outer recirculation zone for \( r \geq 50 \) mm) and the NO mole fraction in the inner recirculation zone was larger, but close to that measured in the exhaust at \( P_0 \) (see Fig. 2).

Radial profiles of NO mole fraction (red) and OH* chemiluminescence intensity (black) were then compared. Figure 6 plots these profiles for height \( P_1 \) (\( z/D = 0.5 \) and \( z = 20 \) mm) and for the same six flames in Fig. 5.
In comparing NO mole fractions and OH* chemiluminescence intensity profiles, two observations were made:

- The location of peak OH chemiluminescence intensity matched that of large NO mole fraction gradients; this was expected because both were indicators of a reaction layer.
- Overall, the peak OH* chemiluminescence intensity seemed to correlate well with the peak NO mole fraction. The peak normalized OH* chemiluminescence intensity increased from around 0.04 to around 0.62 between flames with $X_{\text{NH}_3} = 0.70$ and $\phi = 0.40$ and $X_{\text{NH}_3} = 0.90$ and $\phi = 0.85$, respectively. This corresponded to a 15.5× increase. In comparison, the peak NO mole fraction increased from 400 ppm to around 6000 ppm, corresponding to a 15× increase. This is an interesting feature, examined more fully in Fig. 7.

Figures 7a and b respectively, plot the normalized global NO measured in the exhaust and peak NO mole fraction at $z = 20$ mm as a function of the normalized averaged OH* chemiluminescence intensity for the experiments adopted from Fig. 2. The monotonic relationship between these two
quantities is clearly evidenced, except at the end of both curves (in the red rectangles), corresponding to $\phi > 0.85$ (right end) or $X_{NH3} < 0.20$ (left end).

Results of 1-D FPF simulations obtained for a greater range of ammonia mole fraction and equivalence ratio are shown in Figs. 7c-d. For $\phi = 0.50$ and $\phi = 0.65$, the normalized peak NO mole fraction increased--but non-linearly--with normalized peak OH* chemiluminescence intensity if $0.25 \leq X_{NH3} \leq 0.70$. For $X_{NH3} = 0.80$ and $X_{NH3} = 0.90$, the normalized peak NO mole fraction also increased non-linearly with normalized peak OH* chemiluminescence intensity, except for $\phi > 0.90$.

While measured and computed OH* vs NO curves did not overlap, these demonstrate that local OH* chemiluminescence intensities (measured in the reaction zone) could be related to NO mole fractions (measured in the reaction zone or post reaction zone). Over a wide range of equivalence ratios (roughly $0.40 \leq \phi \leq 0.85$) and ammonia fuel fractions (roughly $0.25 \leq X_{NH3} \leq 1.00$), the trends of NO mole fractions were recovered qualitatively using only OH* chemiluminescence images.

Figure 7: Normalized (a) NO measured in the exhaust and (b) peak NO measured at $z = 20$ mm; (c)-(d) computed normalized NO mole fraction, as a function of normalized OH* chemiluminescence intensity. Each data point corresponds to a different equivalence ratio/ammonia fuel fraction couple.
This is an important finding because OH* chemiluminescence measurements are non-intrusive and relatively cheap. This method could be used to examine NO emission of combustors as long as some optical access is available. Note that a correlation between NO and ground state OH radical had been shown before by others [7, 8, 11]. However, measuring ground state OH, usually achieved using OH-PLIF, in industrial combustors is not realistic. Also, correlation between NO and OH did not guarantee correlation between NO and OH* because ground state OH and excited OH* are produced via different routes.

As shown in Figs. 3 and 7, this method cannot be applied to equivalence ratios larger than $\phi = 0.90$, where the NO mole fraction drops while that of OH* increases. This is because, close to stoichiometric and rich, reaction $\text{NH}_2 + \text{NO} = \text{N}_2 + \text{H}_2\text{O}$ [7] kicks in due to the abundance of NH$_2$ and NO is rapidly consumed. For this reason, the curve plotting NO vs OH* ceases to be monotonic (see Fig. 7). This method is also expected to fail for ammonia fuel fractions smaller than $X_{\text{NH}_3} \approx 0.25$, because chemical pathways leading to the formation of NO gradually shift from fuel NOx pathways to thermal NOx pathways and more closely resemble that found in a pure hydrogen flame.

6. Concluding Remarks

The NO and OH* emission characteristics of hydrogen-enriched ammonia-air flames were investigated experimentally and numerically. The main findings were as follows:

- Using very lean equivalence ratios ($\phi \approx 0.40$) diminished NO emissions for a large range of ammonia fuel fractions (at least from $0.50 \leq X_{\text{NH}_3} \leq 0.80$). NO exhaust mole fractions could be as low as 100 ppm--very low compared to NO mole fractions typically reported for slightly lean and stoichiometric ammonia-air flames.
- For larger lean equivalence ratios (at least up to $\phi = 0.65$), good NO emission performance could still be achieved, but large ammonia fuel fractions were required. For $\phi = 0.65$, the minimum desired ammonia fuel fraction is $X_{\text{NH}_3} = 0.90$. Therefore, the
range of conditions yielding low NO emissions may be restricted by the blow-out limits of the combustor.

- There was a monotonic relationship between OH* chemiluminescence intensities (measured in the reaction zone) and global NO mole fractions (measured post reaction zone) for a large range of equivalence ratios ($0.40 \leq \phi \leq 0.90$) and ammonia fuel fractions ($0.25 \leq X_{NH3} \leq 0.90$). Within this range, non-intrusive, relatively cheap OH* chemiluminescence experiments could be used instead of intrusive, or more challenging local NO mole fractions measurements, to study the NO emission characteristics of combustors fuelled with hydrogen-enriched ammonia blends.

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References


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