

Stability Limits and Transfer Functions of Partly Dissociated Ammonia Flames

Nader N. Shohdy, Mhedine Alicherif and Deanna A. Lacoste.
CCRC, King Abdullah University of Science and Technology (KAUST)
Mechanical Engineering Program, Physical Science and Engineering Division, KAUST
Thuwal, Saudi Arabia

1 Introduction

In the global stance of reducing greenhouse gas emissions, carbon-free fuels including ammonia are viewed as alternatives to hydrocarbon fuels for combustion processes. Ammonia has the advantage of high mass density at ambient temperature and relatively low pressures. Thus, the storage and transportation of ammonia are easier compared to other carbon-free fuels [1, 2] making it competitive for gas turbine engine applications. The main on-going challenges of burning ammonia are a low burning velocity, a narrow flammability range, and a large production of nitric oxides [3,4]. Recent studies have shown that dissociation of a fraction of ammonia into hydrogen and nitrogen prior to combustion is very promising. For example, notable enhancement in stability limits for turbulent ammonia-hydrogen flames has been seen in [4] by increasing hydrogen content in the mixture. Very lean ammonia-hydrogen flames showed promising NO mole fractions kept to around 100 ppm [4].

For gas turbine applications, another important phenomenon to consider are the thermoacoustic instabilities. If the flame is very responsive to acoustic perturbations of the incoming flow, thermoacoustic instabilities can emerge. The response of hydrocarbon-air swirl flames to acoustic modulation of the flow has been extensively studied [5–11]. For swirl flames, the flame response to perturbations is controlled by the flame roll-up around a vortex shed in the shear layer at the exit of the injection tube (flame vortex roll-up) and the swirl number fluctuation.

Recently, Wiseman et al. [12] showed that partially dissociation ammonia premixed flames may be more prone to thermoacoustic instabilities than methane flames for a wider range of acoustic frequencies. However, only substantial percentages of ammonia dissociation were taken into account in their investigation, thus the specific degree of hydrogen addition to create a responsive flame was not looked into.

This work aims at evaluating the impact of ammonia dissociation degree on lean blow-off, pollutant emissions, and sensitivity to thermoacoustic perturbation of the flame. This investigation is carried out in a swirl burner at atmospheric pressure, with a 3.4-kW thermal power.

2 Experimental Setup and Diagnostics

Detailed description of the setup used can be found in [10, 11]. It includes an acoustic forcing system installed on an atmospheric pressure swirl stabilized burner. The radial swirler with a 1.67 swirl number (calculated based on [13]) generates a swirling flow that stabilizes the flames over a conical shape bluff

body of 10 mm diameter. The flame is contained in a quartz tube with an inner diameter of 70 mm and a length of 200 mm. Four different fuels were investigated: pure ammonia as baseline and three mixtures of NH_3 , H_2 and N_2 , emulating the levels of ammonia thermal dissociation. The dissociation degree α is defined as:

$$\alpha = \frac{Y_{\text{H}_2} + Y_{\text{N}_2}}{Y_{\text{NH}_3} + Y_{\text{H}_2} + Y_{\text{N}_2}},$$

with Y_{H_2} the mass fraction of hydrogen, Y_{N_2} the mass fraction of nitrogen, and Y_{NH_3} the mass fraction of ammonia. The mixtures that were studied in this work correspond to 0%, 10%, 20%, and 28% dissociation. The maximum dissociation of 28% was selected because its flammability limits are similar to those of methane-air flames [14]. For a bulk flow velocity of 7 m/s and an equivalence ratio of 0.95, the mass flow rates of the gases for each of the four mixtures are listed in Table 1. The burner was supplied with a perfectly premixed flow of the gases. For these conditions, the flame thermal power for adiabatic combustion was about 3.4 kW, while the Reynolds number was kept at 4500.

Table 1: Mass flow rates for the fuel-air blends utilized for the measurements of the FTFs.

Condition	Ammonia, SLPM	Hydrogen, SLPM	Nitrogen, SLPM	Air, SLPM
0% Dissociation	15.53	0	0	58.36
10% Dissociation	13.69	2.28	0.76	57.15
20% Dissociation	11.92	4.47	1.49	56.01
28% Dissociation	10.56	6.16	2.05	55.12

To better characterize the effect of ammonia dissociation on the NO_x emissions and on the response of the flame to acoustic perturbations, the following measurements were performed: axial velocity, OH^* chemiluminescence imaging, average NO and NO_2 concentrations in the exhaust gases. To determine the acoustic forcing of the incoming flow, a hot wire anemometer was used 1.5 cm upstream of the swirler. The hot wire was calibrated for each of the four mixtures due to the significant variation in the thermal conductivity and density of the gases. Quantifying the flame's reaction to acoustic flow modulation requires the acquisition of HRR fluctuation. Chemiluminescence of OH^* was used as a marker of HRR since the gases were perfectly premixed. The flames' light emission was focused using a convex lens (75-mm focal length) onto a photomultiplier tube that was fitted with a bandpass filter centered at 310 nm, with a FWHM of 10 nm. Finally, a gas analyzer with NO , NO_2 and O_2 sensors was used to examine the composition of the exhaust gases. The uncertainty in the concentration measured was about ± 5 ppm for measured values between 0 and 99 ppm, $\pm 5\%$ of measured value between 100 and 1999 ppm, and $\pm 10\%$ of measured value between 2000 and 4000 ppm for NO ; ± 5 ppm for measured values between 0 and 99 ppm and $\pm 5\%$ of measured value between 100 and 500 ppm for NO_2 , and $\pm 0.8\%$ for O_2 .

3 Results

Examples of direct visualization of the four flames obtained with the mass flow rates summarized in Table 1 are shown in Figure 1. These images were captured with a DSLR camera. Ammonia dissociation reduces the flame length, from more than 12 cm for pure ammonia to less than 4 cm for 28% dissociation, making the flames more compacted for the same thermal power.

In the range of bulk velocities between 4 and 13 m/s, the impact of ammonia dissociation on the lean blow-off limit was examined. The equivalence ratio at lean blow-off for the four percentages of dissociation as a function of the bulk flow velocity are shown in Figure 2.

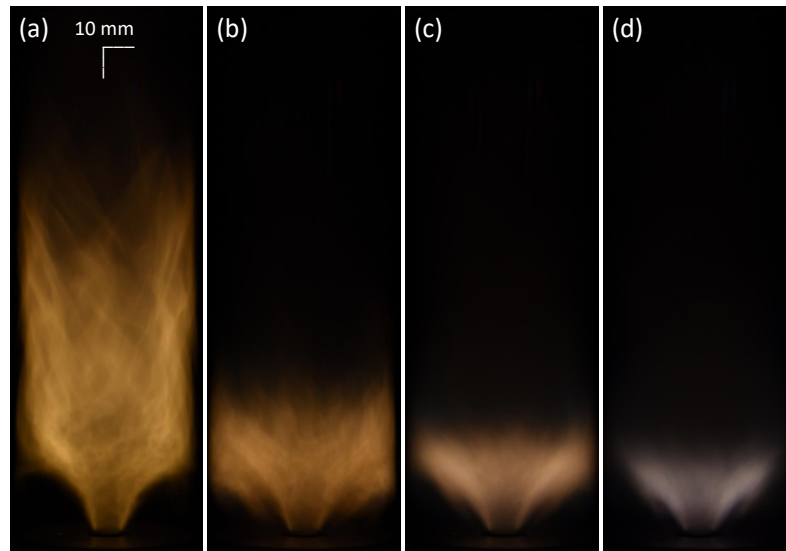


Figure 1: Direct visualization of (a) NH_3 0% dissociation, (b) NH_3 at 10% dissociation, (c) NH_3 at 20% dissociation, and (d) NH_3 at 28% dissociation flames, with a thermal power of 3.4 kW, a bulk flow velocity of 7 m/s, an equivalence ratio of 0.95.

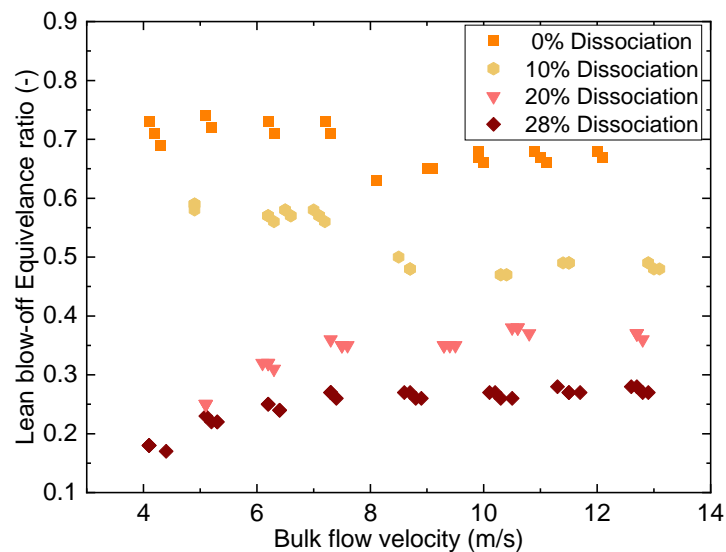


Figure 2: Equivalence ratio at blow-off as a function of the bulk flow velocity of ammonia at 0%, 10%, 20%, and 28% dissociation degree.

Flames with a higher hydrogen content were more resistant to blow-off than those with little to no hydrogen as obtained in Khateeb [4]. The equivalence ratio at blow-off for 20% and 28% dissociation is monotonically rising with the bulk flow velocity until 8 m/s. Alternatively, for velocities larger than 8 m/s the blow-off plateaued. The equivalence ratio at blow-off is nearly constant for pure ammonia and ammonia at 10% dissociated flames, but at lower bulk flow velocities, in the 4–7 m/s range. The equivalence ratio decreases during blow-off at around 8 m/s, then slowly increases with the velocity. This behavior points to various stabilizing strategies at both low and high flow velocities.

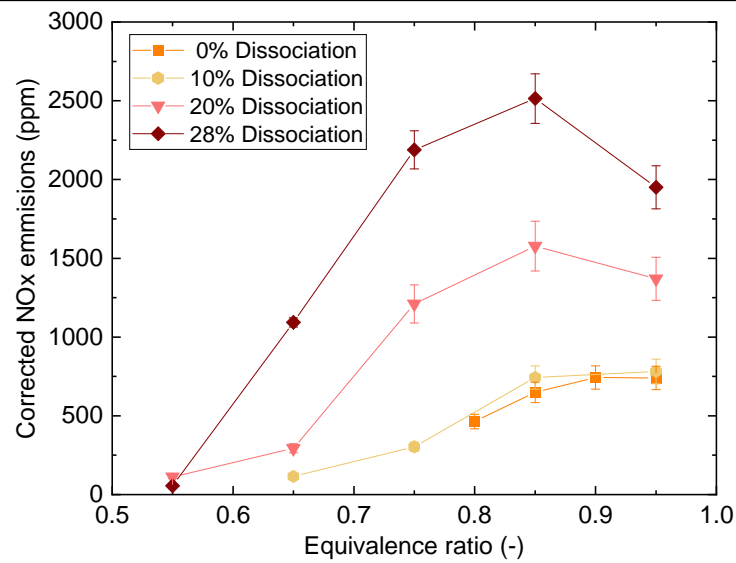


Figure 3: Corrected concentration of NOx, as a function of the equivalence ratio for ammonia flames at 0%, 10%, 20%, and 28% dissociation degree.

Figure 3 presents the corrected concentration of NOx, including both NO and NO₂, as a function of the equivalence ratio for ammonia flames at 0%, 10%, 20%, and 28% dissociation degree. A correction was performed to not underestimate the amount of NOx produced per unit of fuel burned in lean cases, due to dilution by air. The reference oxygen concentration is taken at 15%, as a representative concentration in burned gases of gas turbine engines [15]. At 10% of ammonia cracking, the effect on the NOx concentration is negligible, with an increase of less than 2%. However, for larger percentages of ammonia cracking, i.e., for $\alpha = 20\%$ and $\alpha = 28\%$, the concentration of NOx in the burned gases increased significantly.

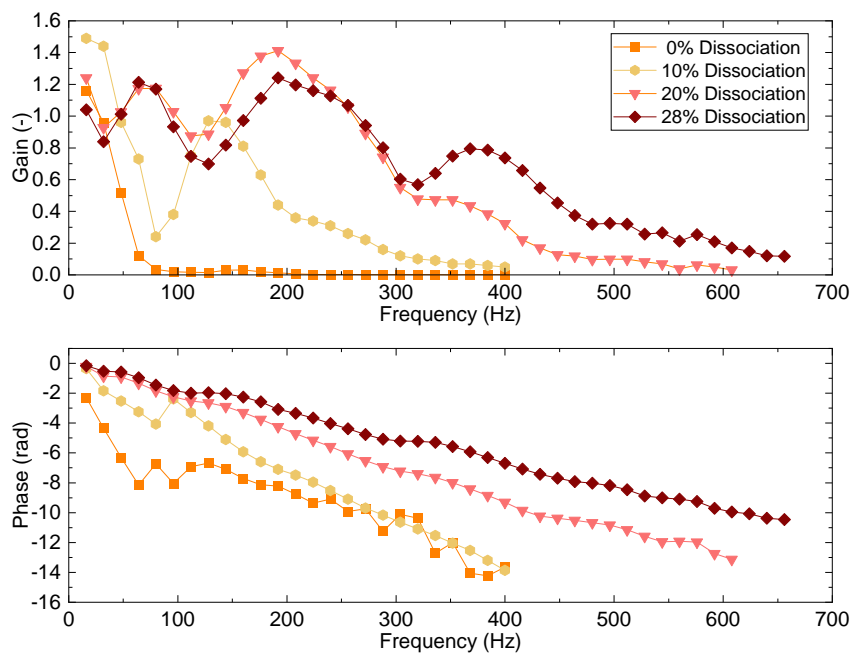


Figure 4: Transfer functions of ammonia flames with 0%, 10%, 20%, and 28% dissociation degree. For all flames, the equivalence ratio was 0.95 and the bulk flow velocity was 7 m/s.

Figure 4 shows the gain and phase of the flame transfer functions (FTF) for a bulk flow velocity of 7 m/s and 0.95 equivalence ratio of pure ammonia and partially dissociated ammonia flames, which corresponds to the conditions listed in Table 1. The range of frequencies taken into consideration was 16 to 670 Hz. Pure ammonia flames responded significantly (gain larger than 1) only for frequencies below 50 Hz. On the other hand, ammonia flames with dissociation were noticeably more sensitive. Two local peaks at 32 and 128 Hz, a local minimum at 80 Hz, and an almost linear phase reduction were reported for 10% dissociation. This is characteristic of methane-air swirl flame transfer functions like those investigated in [10–12]. Multiple local maxima and minima was observed for higher ammonia dissociation degree, however the phase remained linear with a decreasing angle as the degree of dissociation increases.

4 Conclusion

The effect of ammonia dissociation on the lean blow-off limit, NO_x emissions, and response of the flame to acoustic forcing of the flow was investigated, at atmospheric pressure. For pure ammonia and ammonia at 10% dissociation, the equivalence ratio at lean blow-off did not follow a monotonic trend, when the bulk flow velocity was increased from 4 to 13 m/s. A step at about 8 m/s was observed. While ammonia dissociation was effective in increasing the lean blow-off limit, the concentration of NO_x in the burned gases was increased by about a factor of two, at 28% dissociation. In parallel, the response of the flame to acoustic forcing was also enhanced for a large range of frequencies, making these flames more prone to thermoacoustic instabilities than pure ammonia flames.

Acknowledgments

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