

Studies on the Combustion Characteristics of Ammonia in a Swirl Combustor

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1 Introduction

Hydrogen (H_2) has been considered as a carbon-free, eco-friendly fuel, but there are obstacles to its practical use, e.g., a problem of storage and transportation due to its low density. Ammonia (NH_3) can be considered as a competitive carbon-free fuel. Compared with H_2 , NH_3 has a lower condensation pressure (8.8 atm) at normal temperature and thus the storage and transportation problem of H_2 can be resolved [1]. Therefore, there have recently been various studies to find the ways to use NH_3 as a fuel, e.g., [2–5]. However, some technical challenges such as the low reactivity of NH_3 and the excessive nitrogen oxides (NO_x) emissions of NH_3 combustion should be resolved for practical utilization of NH_3 as a fuel. To overcome these problems, the combustion of NH_3 blends (NH_3 -methane (CH_4) and NH_3 - H_2 blends) and pure NH_3 under oxygen (O_2)-enriched conditions were suggested and their fundamental combustion characteristics have been studied in this laboratory [6–13]. For practical applications of NH_3 as a fuel, further studies in addition to the fundamental combustion characteristics of NH_3 blends and O_2 -enriched pure NH_3 are needed and thus their combustion properties in a swirl combustor are investigated in the present study. The combustion stability limits and NO_x emissions under normal temperature and pressure (NTP, 298 ± 3 K and 1 atm) condition are measured and predicted.

2 Experimental and Computational Methods

The experimental apparatus in the present study is composed of a combustor with a swirl injector, a reactants supply system for NH_3 (purity > 99.9999%), CH_4 (purity > 99.999%), H_2 (purity > 99.999%), O_2 (purity > 99.95%) and N_2 (purity > 99.95%) with mass flow controllers (MKP VIC-D220, VIC-D240; accuracy: $\pm 1\%$ of full scale), a data acquisition system (NI 9239, NI 9269) for collecting data, a digital camera (Sony A6000) for direct images of flame, a pressure gauge (DPG3500) and a gas analyzer (Testo 350K) to measure the NO_x concentration of exhaust gas as shown in Fig. 1. The combustor is made of stainless steel 316L which is an anti-corrosive material. A combustion chamber with the volume of $45\times 45\times 240$ mm³ is designed to endure the maximum pressure of 10 bar and has four optical quartz windows with the visible area of 35×240 mm² for flame visualization. The swirl injector is located on the bottom of the combustor and the swirl number (S_N) is fixed with a value of 0.456. S_N is defined as follows [14]:

$$S_N = \frac{2}{3} \left[\frac{1 - (D_i / D_o)^3}{1 - (D_i / D_o)^2} \right] \tan \alpha$$

where D_i is the injector inner diameter, D_o is the injector outer diameter and α is the swirl vane angle.

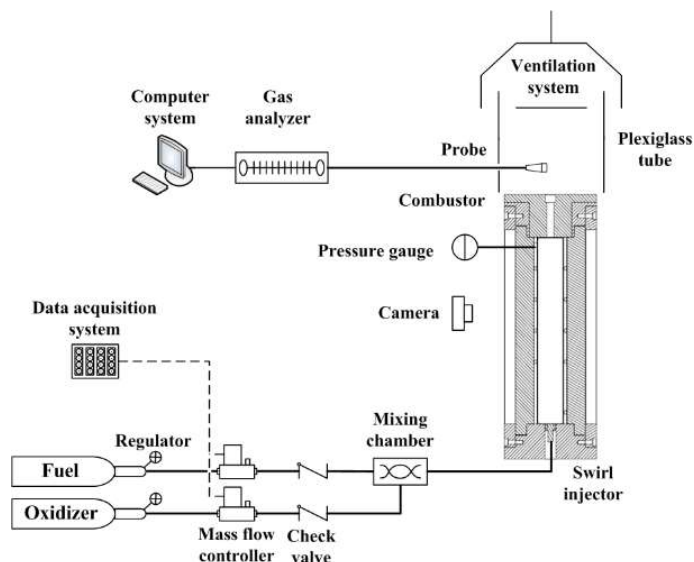


Figure 1: Schematic of experimental apparatus.

The combustion characteristics of $\text{NH}_3\text{-CH}_4/\text{air}$, $\text{NH}_3\text{-H}_2/\text{air}$ and O_2 -enriched NH_3/air premixed flames at NTP are investigated at the conditions where reasonable burning intensity for practical applications is expected from the previous fundamental studies in this laboratory [7,12,13]: 0.80 for the mole fraction of CH_4 in the fuel blends (x_{CH_4}), 0.35 for the mole fraction of H_2 in the fuel blends (x_{H_2}) and 0.35 for the mole fraction of O_2 in the nonfuel mixture (x_{O_2}). Combustion stability limits are determined when extinction (i.e., blowout) occurs with varying the injection velocity u and the fuel-equivalence ratio ϕ . The concentration of NO_x is measured at 40 cm from the combustor outlet for $u = 5$ m/s condition. Computations to predict NO_x concentrations for comparison with the measured results are also conducted using the PREMIX code that was developed by Kee et al. [15] with three detailed reaction mechanisms: Smith et al. [16] for $\text{NH}_3\text{-CH}_4/\text{air}$ premixed flames (C/H/N/O reactions, 53 species and 325 reversible reactions), Miller and Bowman [17] for $\text{NH}_3\text{-H}_2/\text{air}$ premixed flames (H/N/O reactions, 19 species and 73 reversible reactions) and Gotama et al. [18] for O_2 -enriched NH_3/air premixed flames (H/N/O reactions, 26 species and 119 reversible reactions).

3 Results and Discussion

Figure 2 shows the direct images of NH_3 premixed flames of $\phi = 1.0$ and $u = 5$ m/s. Orange chemiluminescence with NH_3 addition is observed due to the NH_2 ammonia α band and superheated H_2O vapor spectra [19].

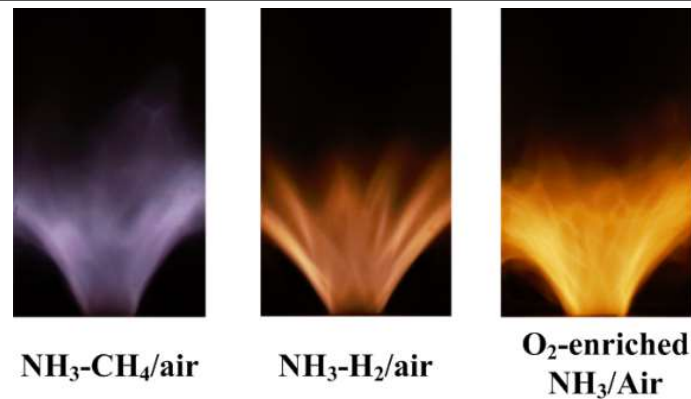


Figure 2: Direct images of NH₃ premixed flames at NTP.

Figure 3 shows the combustion stability limits of NH₃ premixed flames at NTP. Although the stability limits of NH₃-CH₄/air premixed flames are narrow compared with the NH₃-H₂/air and O₂-enriched NH₃/air (NH₃/O₂-N₂) premixed flames due to the low reactivity of NH₃, the stable region providing reasonable burning intensity with reduced carbon dioxide (CO₂) emissions compared to the pure CH₄/air premixed flames [12] could be found. In the case of NH₃-H₂/air premixed flames, the low reactivity of NH₃ is compensated with H₂ substitution in NH₃/air flames [10] and the combustion stability limits are broader than the NH₃-H₂/air and O₂-enriched NH₃/air premixed flames. The combustion stability limits of O₂-enriched NH₃/air premixed flames are also broadened compared with the NH₃-CH₄/air premixed flames since the low reactivity of NH₃ is improved by O₂ enrichment [13].

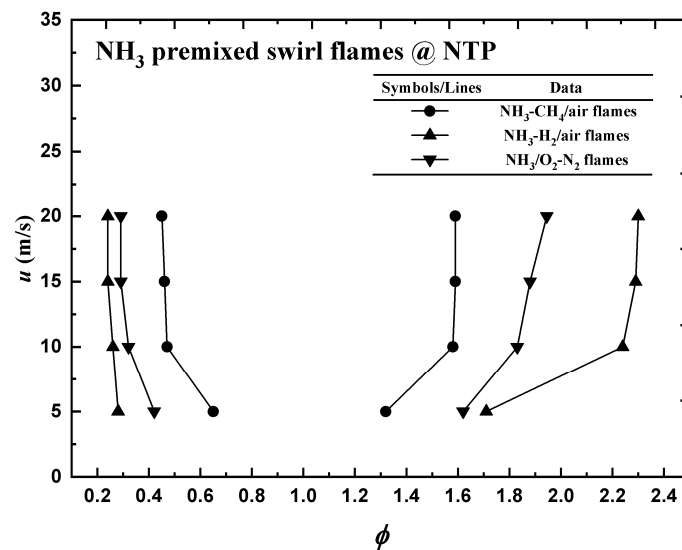


Figure 3: Measured combustion stability limits of NH₃ premixed flames at NTP.

Figure 4 shows the measured NO_x emissions and the predicted NO_x mole fraction X_{NO_x} for the NH₃ premixed flames at NTP. The NO_x emissions are the sum of the NO and NO₂ concentration and converted to the case that the mole fraction of O₂ in the mixture is 16%. X_{NO_x} is the sum of the NO and NO₂ mole fractions at the point where the maximum NO mole fraction is predicted. The measured results show that NO_x emissions in the NH₃ premixed flames are significantly high at fuel-lean condition, and the NO_x emissions reach up to 800 ppm. At fuel-rich condition, however, they are low compared with the fuel-lean conditions due to the deNO_x effects of unburnt NH₃ [6]. Meanwhile, the predicted X_{NO_x} is

much higher than the measured NO_x emissions, though it shows a similar tendency. Of course, this quantitative difference is observed since the predicted result is obtained where the maximum NO mole fraction is found in the flame and does not directly imply the exhaust gas composition. Although the measured NO_x emissions are much lower than the predicted X_{NO_x} , they exhibit excessive values compared with the hydrocarbon/air flames, e.g., CH_4/air flame, and thus should be reduced by adopting various NO_x reduction technologies such as selective catalytic reduction (SCR) [3] for practical applications of NH_3 as a fuel.

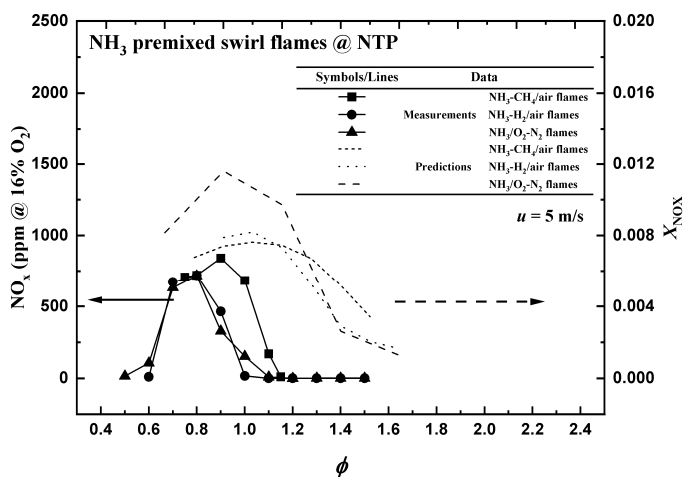


Figure 4: Measured NO_x emissions and predicted X_{NO_x} of NH_3 premixed flames at NTP.

4 Conclusions

In order to investigate the possible use of NH_3 as a fuel, the combustion stability limits and NO_x emissions of $\text{NH}_3\text{-CH}_4/\text{air}$, $\text{NH}_3\text{-H}_2/\text{air}$ and O_2 -enriched NH_3/air premixed flames at normal temperature and pressure under the conditions where reasonable burning intensity for practical applications is expected have been investigated using a swirl combustor. Although the combustion stability limits of $\text{NH}_3\text{-CH}_4/\text{air}$ premixed flames are the narrowest among the present flames due to the low reactivity of NH_3 , they are expected to have reasonable burning intensity with reduced CO_2 emissions. The low reactivity of NH_3 has been improved by H_2 substitution or O_2 enrichment and thus $\text{NH}_3\text{-H}_2/\text{air}$ and O_2 -enriched NH_3/air premixed flames show broadened combustion stability limits. Due to the role of excessive NH_3 as a deNO_x agent, NO_x emissions are relatively low at fuel-rich condition for all the present flames. Since the maximum NO_x concentration in the present test conditions reaches up to 800 ppm, however, further studies are needed to obtain an additional database required to develop NH_3 combustion devices with appropriate levels of NO_x emissions, which could include flame visualization and tests under pressurized condition and are in progress.

5 Acknowledgment

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