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A study on the impact of elevated air temperatures on flame stability and NOx emissions of methane-ammonia-air mixtures in a premixed swirl combustor

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Abstract: Emissions from power generation is a major concern relating to pollution and climate change, and a number of pathways are being explored that utilize carbon-neutral fuels or generate net-zero lifecycle emissions. Ammonia is a promising alternative to hydrocarbon-based fuels, capable of being used as a stand-alone fuel in gas turbine combustion or in combination with natural gas. Results from a recent study utilizing mixtures of methane-ammonia-air mixtures in a premixed swirl combustor showed the potential to lower the lean-blowout limit by using distributed fuel injection approach. Concurrently the lean mixture showed potential to reduce NOx emissions while operating at high ammonia content. The current study will attempt to further reduce the lean limit and operate at higher ammonia content (>80%) by increasing inlet air temperature. Previous studies have shown the ability to increase flame stability by achieving a higher flame speed using elevated inlet air temperatures ranging from 323—423 K. Experiments will be accompanied by a reactor-network model built on ANSYS-Chemkin and its results will be used to gain insight into reaction pathways, adiabatic flame temperature and flame speed, which are critical factors affecting combustor performance and emissions. NOx emissions will be quantified using measurements from an exhaust gas analyzer. The effect of preheating inlet air on NOx emissions and lean blowout limits will be studied.

Keywords: Ammonia, Swirl combustion, Lean blowout, NOx emissions

1. Introduction

Ammonia is a carbon-free molecule that has the potential to provide an alternative fuel pathway to reduce green house gas emissions generated by hydrocarbon fuels [1]. Renewable energy sources can be used to generate Ammonia avoiding the energy intense Haber Bosch process thus ensuring a lower lifecycle GHG emission [2]. However, direct use of Ammonia for power generation in a gas turbine combustor is challenged by low flame speed and issues with flame stability [3]. These issues limit the lean blowout limit (LBO) for ammonia-air flames which is undesirable from a soot and combustion efficiency standpoint. Efforts have been made to improve the combustion characteristics of Ammonia by adding methane to the mixture. While the addition of methane has resulted in improved flame stability and hence the LBO, NOx emissions have been found to be significantly higher than those from conventional fuels such as natural gas. A recent study by this group considered the use of a novel swirler configuration to improve fuel-air mixing facilitating further reduction in LBO with higher ammonia content in the flame enabling lower NOx emissions. The study was conducted in a model swirl combustor at ambient air inlet conditions. The particular novelty of the swirler was its ability to improve fuel-air mixing and thereby improve lean blow out characteristics. Improvement in mixing was achieved by a distributed injection technique whereby fuel was injected into crossflowing air moving over the swirler vanes using a large number (>1000) of injection holes. Figure 1 shows a schematic of the injection approach along with the architecture of the swirler, referred to as the Micro Fuel Injection Swirler (MFIS) [4]. Improvement in mixing is facilitated by increase in the momentum flux ratio along with generation of fine-scale turbulence in the injection zone. Measurements carried out on a model combustor equipped with the novel swirler architecture found LBO limits to be lowered to equivalence ratios between 0.65-0.7. These LBO limits were achieved with ammonia content as high as 80-90% by volume. Measurement trends showed that NOx emissions could be potentially further reduced by increasing the ammonia content in the mixture if the LBO limits could be suppressed further.

Figure1: Schematic showing the fuel injection process by the MFIS swirler; Details of the swirler.

Flame stability and LBO are significantly impacted by flame speed and ignition delay. These properties are strong functions of mixture chemical kinetics impacted by the fuel chemistry and burner conditions. This study extends previous work by attempting to further suppress LBO limits for methane-ammonia-air mixtures by preheating inlet air going into the combustor. The effect of higher inlet temperature resulting in a faster flame speed and reduced ignition delay can potentially lead to suppression of LBO limits in the combustor, while utilizing higher Ammonia content.

The layout of the paper is as follows. The experimental setup used in the investigation of methane-ammonia-air flames using the MFIS injection strategy in a model swirl combustor is described along with the diagnostics employed and test conditions. Next, experimental results are described, and observations are analyzed using results from 1D calculations for flame. Results include measurements of LBO and NOx emissions over a range of test conditions. Reactor-network calculations using detailed chemistry are also examined to understand underlying chemical kinetics. Finally, conclusions are presented along with future research directions.

2. Methods / Experimental

2.1 Micro Fuel Injection Swirler (MFIS): A micro fuel injection swirler (MFIS) is utilized in this work to facilitate improved fuel-air mixing in the model combustor. The swirler shown in the schematic in Fig. 1 incorporates a large number of fuel injection points directly located on the swirler vanes. Air entering the swirler flows over the vanes as well as within through holes located on the vanes. A fuel injection tube located within the central channel supplies fuel to the injection points on the swirler vanes through channels machined within the vanes. This architecture results in the generation of a large number of injection points, more than 1000, where fuel is injected into the cross-flowing air aided by the air flow occurring via the through holes located on the swirler blade. As shown in the close-up photographs of the swirler blades in Fig. 1, each fuel injection hole is surrounded by several holes carrying air flowing through the cross-section of the blade. The shear flow generated by this flow configuration along with the injection of the shear layers into a crossflow of air flowing over the vanes results in the generation of fine-scale turbulence aiding the fuel-air mixing process. The result is a more homogeneously mixed fuel-air mixture which can provide improved resistance to blowout and increase flame stability.

2.2 Combustor

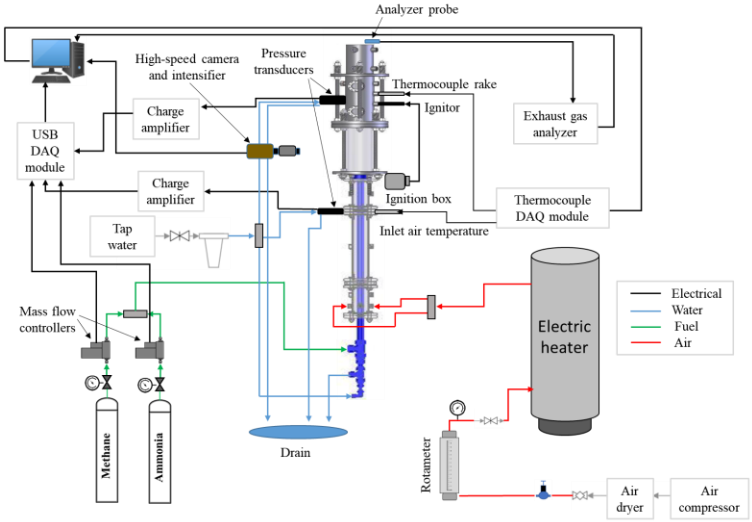

Figure 2: Model swirl combustor test rig schematic

A model combustor setup is used to conduct tests with methane-ammonia-air mixtures using the MFIS swirler as discussed in the previous sub-section. Figure 2 shows a schematic of the experimental setup. Compressed air from an external high-capacity compressor flows through a dryer and flowmeter before entering a high-flow capacity electric heater (Chromalox circulation heater). Heated air flows through insulated metal pipes before entering the upstream section of the model combustor. Fuel comprising of methane and ammonia mixtures is supplied from compressed air cylinders. Mass flow controllers (Omega FMA 5400), controlled through a Labview program are used to set the fuel-air mixture ratio. The fuel mixture enters the model combustor at the upstream section through a concentric pipe located with the air flow section. Fuel and air move through the upstream section and enter the swirler region where the MFIS as shown in Fig. 1 is used to generate a fuel-air mixture exiting 0.5 inches upstream of the dump plane of the combustor. A high voltage ignition source provides the ability to ignite the fuel-air mixture. An optically accessible chamber is used to visualize the combustion process and swirl flame using different diagnostic techniques. The swirler is cooled by cooling water supplied through channels located just outside the fuel channel.

2.3 Diagnostics

2.3.1 Emissions Analyzer: The model combustor exhaust is sampled using an Enerac model emissions analyzer. The analyzer which utilizes non-dispersive infrared (NDIR) technology can measure emissions of 5 gases, CO, NO, NO2, SO2, and O2 simultaneously. A probe with a built-in temperature sensor is connected to the exhaust from the combustor at a location of about 60 cm downstream of the dump plane. Measurements from the analyzer are sent to a computer where it is logged by the analyzer software at a rate of 60 Hz. The analyzer has an accuracy of ±2%

2.3.2 Data acquisition and control: Gas mass flow controllers operate on a 0-5 VDC analog voltage signal generated using a National Instruments (NI) USB-6343 multi-function data acquisition and control device (DAQ). A LabVIEW program running at 1 Hz is used to cycle through the test cases and send required output voltage to the mass flow controller.

2.4 Test Conditions

φ	NH3 volume %	CH4 volume %	Air flow rate	Inlet air temperature	Power output, kW
0.7-0.8	20-80	80-20	10	50	12-20
			SCFM	Deg C	

Table 1: Test conditions

Table 1 summarizes the overall range of variation of different parameters explored in this work. All measurements are carried out at ambient pressure conditions.

2.5 Chemical reactor network simulations

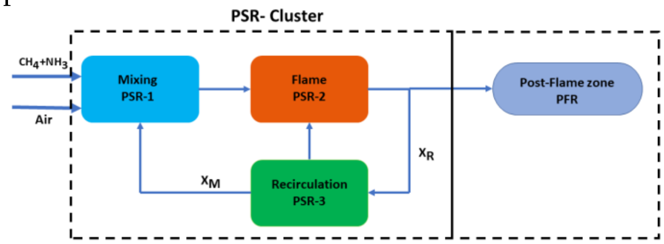

Figure 3: Chemical reactor network representing the MFIS-equipped swirl combustor.

Chemical reactor networks consist of a group of chemical reactors such as a perfectly stirred reactor (PSR) and plug flow reactor (PFR) that are arranged in such a manner that they incorporate simplified effects of fluid dynamics in the combustion chamber on detailed chemical kinetics and as a group, reproduce the overall combustion process. This concept, initially introduced by Bragg [5] and since used by a number of research studies [6, 7], is applied in the current case to study the combustion process using the MFIS swirler. Figure 3 shows the chemical reactor network used in the present study. In previous studies [6], results of detailed CFD calculations and experimental observations/ measurements are utilized to build the reactor network. In this work, we present an initial study utilizing a reactor network configuration used in previous work by Valera-Medina [7] to study an ammonia-methane-air flame in a premixed swirl combustor. Recirculation and combustion processes in the swirl combustor are modelled by the PSR reactor cluster. The fraction of mass transferred between reactors is represented as X_M and X_R. Similar to the pervious simulations of Valera-Medina [7], the fractions, X_M and X_R, for the current simulations are set as: X_M=0.1, X_R=0.3, respectively. Apart from the mass fraction, residence time or volume of each PSR needs to be provided as an input. From CHEMKIN, the residence time is defined as $\tau_j = \frac{\rho V_{PSR,j}}{\dot{M}_{in,J}}$, where $\dot{M}_{in}$ represents the total inlet mass flow rate for the PSR-j (1,2,3) in the cluster and $V_{PSR,j}$ represents its volume. The total volume of the PSR cluster was fixed as ≈585 cm^3, which corresponds to the active combustion volume of the test rig. The volume fractions of individual reactors- Mixing, Recirculation and Flame, were set at 20%, 20% and 60%, similar to the work of Zhang [8]. Using the individual reactor volume and inlet mass flow rates, the residence time can be evaluated using Eq. 1. The length and diameter of Post Flame zone- PFR were set as 11 cm and 8 cm respectively, which again corresponds to the dimensions of the present test rig. The reaction mechanism developed in the work of Okafor et. Al [9], for CH_4-NH_3 fuel, was employed, where in pertinent reaction steps of GRI Mech 3.0 [10] and Tiran [11] reaction mechanisms were combined. From the present experiment test conditions, the volume flow rate of air was set at 0.0047 m^3/s, while volume flow rate of fuel (CH_4+NH_3) was varied based on the equivalence ratio and volume fraction of individual fuels.

3. Results and Discussion

3.1 LBO measurements

The Lean blowout (LBO) limit is a critical parameter in this research. Lean blowout limit as a function of ammonia volume percentage is shown in Fig. 4. The equivalence ratio is decreased until flame blow off is seen. The two curves represent inlet air temperatures of 20°C and 50°C, respectively. The LBO limit increases as the air inlet temperature rises, likely primarily due to increase in flame speed at higher inlet temperatures. The flammability range is widened with the use of inlet air at 50°C. This enabled the combustor to be operated with 90% NH3 by volume in the fuel mixture. Previous investigations using air at 20°C found that flames could not be sustained beyond 85% NH3 by volume.

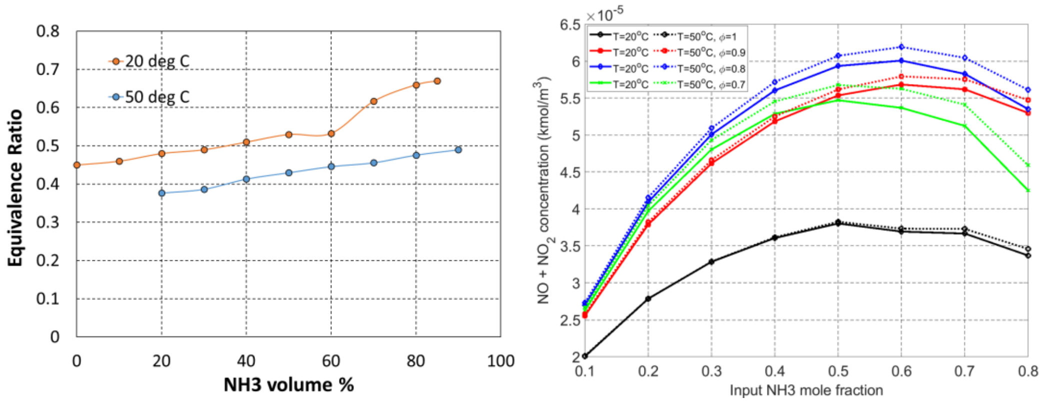

Figure 4: Equivalence ratios corresponding to lean blowout limit as a function of NH3 volume % for inlet temperatures of 20^0C and 50^0C (*Left*); Total NOx concentration as a function of equivalence ratio and NH3 mole fraction for inlet temperatures of 20^0C and 50^0C (*Right*).

3.2 Reactor network results

Figure 4 also shows total NOx generation (NO + NO_2) as a function of NH3 volume % for equivalence ratios between 0.7-1.0. It is seen that the NOx emissions decrease with increase in the equivalence ratio till φ=0.8 and then starts to decrease. It is also seen that for increase in the ammonia addition up to 60%, there is an increase in the NOx generation. The reactor network predicts a reduction in NOx emissions beyond 60% ammonia addition.

3.3 NOx measurements

NOx corrected to 15% O2 measurements are reported in Fig. 5 for two different inlet air temperatures 20°C and 50°C for airflow rate of 10 scfm and 0-90% ammonia addition. It is seen that NOx emissions are higher in cases with higher air inlet temperature for both equivalence ratios reported in this work. This is primarily caused by higher flame temperatures leading to thermal NOx generation. NOx generation increases with increase in the ammonia addition. NOx emissions peaks for ammonia addition between 30% and 50%. It is also seen that beyond 70% ammonia addition the NOx emissions reduce substantially. A sustainable flame was achieved for very high ammonia content cases >90% NH3 using air preheated to 50°C. Results from the reactor network predicts similar NOx emission trends. The use of preheated air leads to higher NOx emissions. However, the use of preheated air opens the possibility of carrying out the combustion process at lean mixture conditions as well with higher NH3 content.

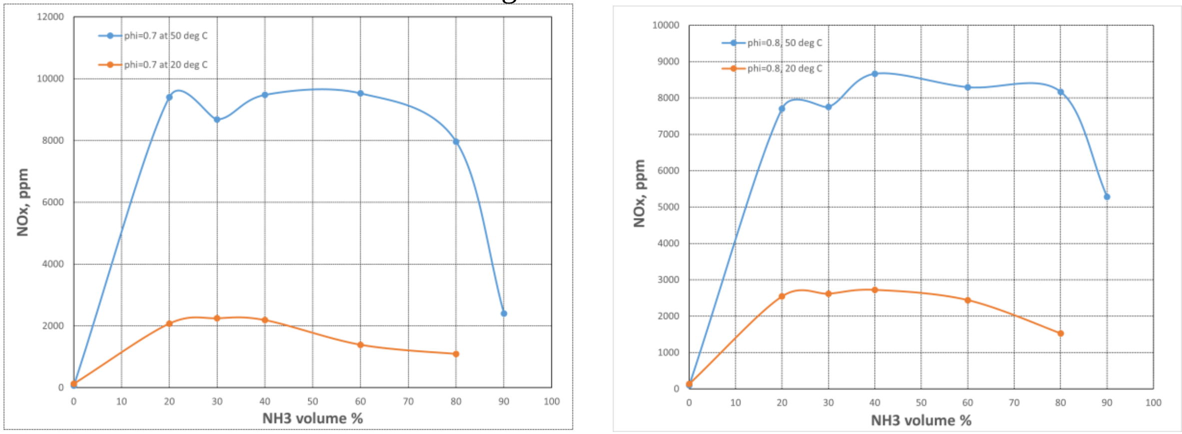

Figure 5: NOx emissions (ppm) for two equivalence ratios (0.7 & 0.8) as a function of NH3 volume % for inlet temperatures of 20^0C and 50^0C.

4. Conclusions

The overall goal of this work is to study the influence of preheating reactants on suppressing lean blowout limit for methane-ammonia-air flames in a swirl combustor and potentially increasing NH3 content in the flame to reduce NOx emissions. Studies were conducted using experiments on a model combustor setup as well as using reactor network models of the same.

- Lean blowout suppression was achieved over a range of NH3 volume % addition by increasing inlet temperature primarily through increases in flame speed. Combustor operational envelope was also broadened, being able to sustain a flame with 90% NH3.
- NOx emissions increased with increasing inlet air temperature likely driven by the increase in thermal NOx generation.
- A reactor network model was successfully employed to predict NOx emission trends consistent with those seen in the experiments.

5. Acknowledgements

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