A Modular Flat-Flame Experimental Platform for Mechanistic Studies of Plasma-Assisted Ammonia/Methane Combustion

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Recent efforts to reduce emissions of NO_x, N_2O, and NH_3-slip in ammonia-methane (NH_3/CH_4) combustion using Nanosecond Repetitively Pulsed Discharges (NRPD) have relied largely on complex plasma-assisted combustion experiments in three-dimensional, turbulent, swirl-stabilized burners. In this work, we introduce a modular experimental platform based on a flat-flame McKenna burner to isolate and study the fundamental plasma-flame interactions that govern NRPD-assisted combustion of NH_3/CH_4/air mixtures. The burner-plasma assembly supports both nanosecond-spark and uniform-discharge operating modes when generating the plasma in the hot exhaust gases. Preliminary NO measurements, with NRPD applied either in the post-flame region or directly within the reaction zone, indicate a net NO penalty under the conditions tested. These results highlight the need for further mechanistic investigation of NRPD-driven chemistry in ammonia-methane flames and its implications for emissions reduction strategies.

I. Introduction

Decarbonization of the energy and transportation industries is a critical step in combating climate change and meeting the rising global energy demand. Central to these efforts is the transition from fossil fuels to carbon-free alternative fuels like hydrogen (H_2) and ammonia (NH_3)[1, 2]. Ammonia is a particularly promising candidate due to the existing global infrastructure for its production, transport, and storage, as well as its relatively high energy density [3, 4]. However, widespread adoption of NH_3 as a fuel is challenging due to its low flame stability, slow laminar flame speed and poor reactivity compared to hydrogen and hydrocarbons [4–6]. NH_3 combustion generates a considerable amount of NO_x and N_2O, both of which contribute to atmospheric radiative forcing. Emissions can reach concentrations on the order of thousands of parts per millions (ppm), far exceeding environmental and regulatory thresholds [4–7]. Effective mitigation strategies are necessary to comply with the regulations.

Plasma assisted combustion (PAC) has emerged as a promising technology capable of addressing the challenges associated with ammonia combustion [8, 9]. PAC has been shown to enhance combustion by decreasing ignition delay time [10], suppressing pressure oscillations in swirl-stabilized burners [7, 11] and extending lean flammability limits [8, 12]. More recently, it has demonstrated benefits in NH_3 and NH_3/CH_4 combustion, including reductions in emissions [7] and extensions of the lean blowoff limits [9]. These findings highlight the potential of PAC for ammonia-based fuels; however, the mechanisms by which plasma affects flame structure, stabilization, and particularly NO_x chemistry, remain insufficiently understood.

A major challenge is that PAC influences nitrogen chemistry differently in ammonia and hydrocarbon systems. In ammonia flames, PAC-generated NH_2 radicals can participate in thermal DeNO$_x$ pathways [4, 9, 13], while in hydrocarbon flames PAC often enhances burning [14, 15] but increases NO_x emissions [7]. This contrasting behavior underscores the need for improved mechanistic understanding of plasma-flame interactions in NH_3/CH_4 mixtures. Understanding is further hindered by the lack of agreement between current kinetic models and experimental measurements. Although one-dimensional modeling of hydrocarbon flames with PAC has been successful [10], current kinetic mechanisms fail to reproduce NO_x emissions in NH_3 combustion [7, 16, 17]. Moreover, reported laminar flame speeds and emissions in NH_3 flames vary significantly across studies [5]. These observations highlight the need for simplified quasi-one-dimensional experimental platforms that can support the validation of chemical kinetic models and enable controlled measurements of key global combustion metrics such as laminar flame speed, extinction strain rate, and emissions.

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This study uses a modular experimental platform based on a McKenna burner to investigate the influence of Nanosecond Repetitively Pulsed Discharges (NRPD) on NO emissions in atmospheric NH_3/CH_4 flames. This canonical laminar flame configuration decouples plasma effects from the complex dynamics of turbulent, swirl-stabilized combustors. The proposed experimental platform provides a fundamental basis for understanding NRPD-flame interactions and supports the development and validation of reduced-order kinetic models for ammonia-based combustion systems.

II. Experimental Setup

The core of the experimental platform is a 60 mm diameter, water-cooled stainless steel McKenna burner (effective area $A_{eff}/A \approx 0.75$) with a stainless steel shroud ring (62.5 mm ID, 73.4 mm OD) from Holthius and Associates. The burner is used to investigate the influence of NRPD on NH_3/CH_4 flames at atmospheric conditions, with a specific focus on NO emissions. McKenna burners generate a uniform, flat (quasi-1D) flame by flowing the premixed fuel-air mixture through a porous plug. They are well suited for studies of both unstrained flames [5] and strained flame configurations [18], the latter achieved by placing a solid plate downstream, providing substantial experimental flexibility.

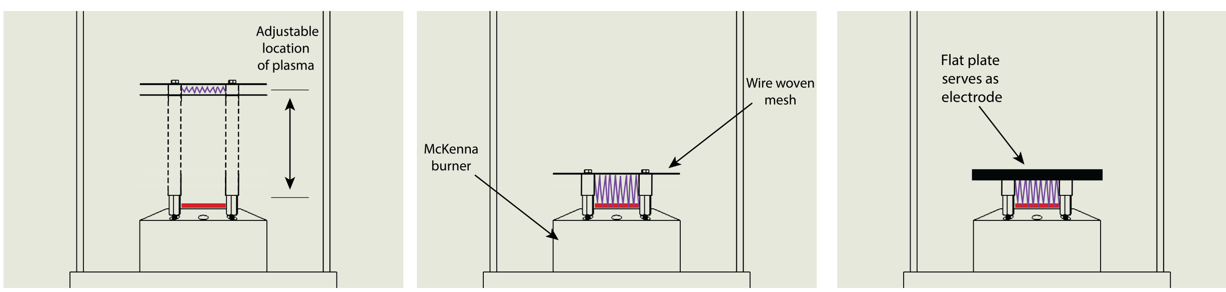
The experimental arrangement supports several configurations, Figure 1:

(a) Unstrained flame with post-flame plasma (Configuration 1): The plasma is applied between two mesh electrodes placed at varying heights above the burner surface (Figure 1a), enabling isolated investigation of plasma effects on exhaust-gas emissions;

(b) Unstrained flame with in-situ plasma (Configuration 2): The plasma is applied between a mesh electrode and the burner surface, with the McKenna burner grounded (Figure 1b), allowing plasma to influence both burning and emissions;

(c) Strained flame with in-situ plasma (Configuration 3): The plasma is applied between a solid stainless steel stagnation plate and the surface of the McKenna burner (Figure 1c), generating a strained flame configuration.

This paper focuses on results from the two unstrained flame configurations (Configurations 1 and 2).



(a) Configuration 1. (b) Configuration 2. (c) Configuration 3.

Fig. 1 Configurations supported by the experimental arrangement. (a) Unstrained flame with post-flame plasma; (b) unstrained flame with in-situ plasma; (c) strained flame with in-situ plama. Red is the flame, purple is the plasma.

A schematic of Configuration 1 is shown in Figure 2. The plasma assembly consists of vertically adjustable, electrically isolated stainless-steel woven-mesh electrodes positioned above the McKenna burner. The mesh has a void fraction exceeding 60% to minimize flow disturbance while serving as the discharge electrodes. The upper (anode) and lower (cathode) electrodes are mounted using a Macor ceramic plate and alumina fasteners, which also provide electrical isolation. Flow rates of air, NH_3, and CH_4 are controlled using Brooks SLA5800 series mass flow controllers. The plasma assembly is mounted on an optical table equipped with a motorized vertical translation stage, allowing fine adjustment of the electrode height relative to the burner surface. Additional coarse adjustment is achieved by repositioning the ceramic mounting hardware. Nanosecond Repetitively Pulsed Discharges (NRPD) are generated using a TPS transient pulse generator (TPS SSPG-20X-HP1 pulser). Both the voltage and pulse repetition frequency (PRF) of the discharge are controlled through the power supply and an external signal generator.

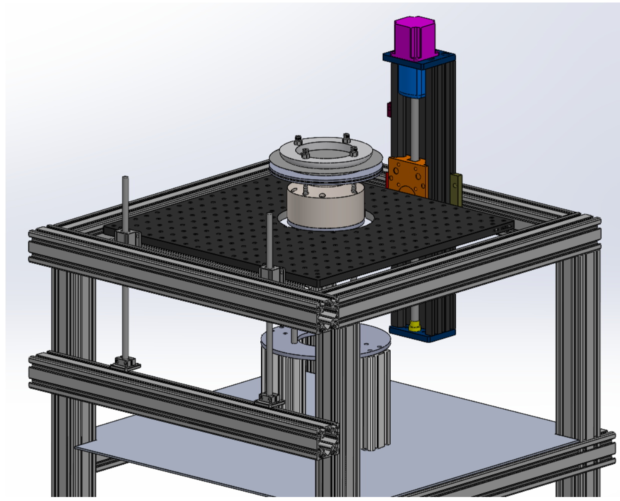
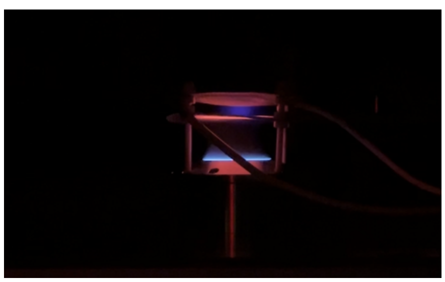


Fig. 2 Schematic of experimental assembly in Configuration 1.

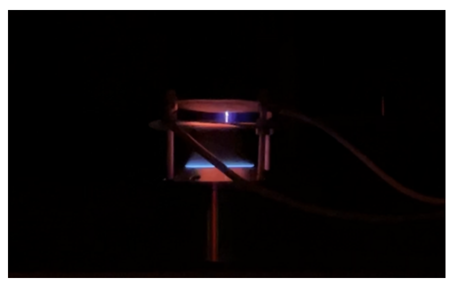
This arrangement enables operation in two discharge modes, Figure 3:

(a) A locally uniform discharge, which preserves the quasi-1D character of the flame and facilitates comparison with 0D and 1D modeling. This configuration exploits the coupling of the plasma to the high temperature of the exhaust gases to generate a uniform plasma as proposed in [19].

(b) A nanosecond spark discharge, which introduces localized and filamentary, high-energy plasma formation similar to that encountered in higher power systems.



(a)



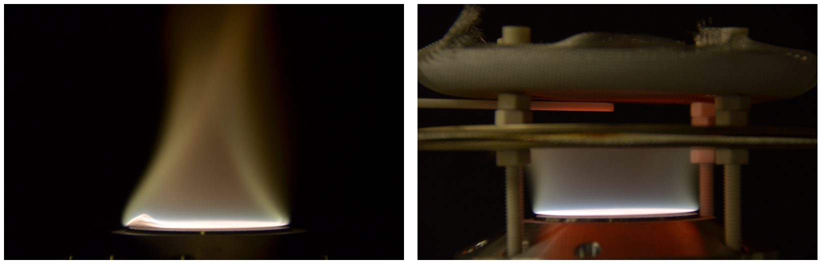
(b)

Fig. 3 Two NRPD discharge modes generated in the burner exhaust of a ϕ = 0.86 CH_4/air flame : (a) locally uniform discharge, and (b) nanosecond spark discharge.

NO concentrations in the exhaust are measured using an INFICON Transpector CPX-100 residual gas analyzer (RGA), capable of detecting species from 1–100 amu. The RGA monitors the peak at $m/z = 30$, corresponding to NO. Calibration is performed using certified gas standards to convert ion currents into partial pressures. Exhaust gases sampled at atmospheric pressure are drawn through a 1.5 m stainless-steel capillary into the high-vacuum instrument. A ceramic tube was added to the end of the capillary to electrically isolate it when sampling between the electrodes.

III. Baseline Flame Characterization

The presence of the electrode assembly above the burner introduces a mild stabilizing effect when the flame operates near its stability limits. Lowering the total flow rate of the burner when increasing the blend percentage of NH_3 ensures the flame remains flat due to the lower laminar burning velocity of NH_3 (7 cm/s) compared to that of CH_4 (38 cm/s) [20]. Under identical flow conditions, flames without the electrode assembly exhibit localized lifting at the burner edge, whereas the assembly suppresses this behavior and maintains a flat, stable flame front, Figure 4.



(a) (b)

Fig. 4 Flame appearance without and with the plasma assembly for a 60% NH_3/ 40% CH_4 blend, ϕ = 1.0: (a) lifted flame at the edges (no plasma assembly); (b) stable flat flame (with assembly).

In addition to the standard unstrained configurations, the burner can operate in a lifted-flame mode in which the flame anchors to the lower electrode rather than the burner surface. In this configuration, NRP discharges can be applied directly within the reaction zone (in-situ) *. This operating mode was explored as a modified version of Configuration 2 to avoid directing nanosecond spark discharges onto the burner surface, which may damage the stainless-steel porous plug.† The experiments reported in this paper for Configuration 2 use this operating mode.

Prior to conducting plasma-assisted combustion experiments, baseline NO measurements were obtained to assess sampling consistency and air entrainment. Measurements taken at two probe heights above the burner surface yielded similar NO mole fractions, indicating minimal dilution from ambient air. The measured NO levels follow the expected trends from existing chemical kinetic mechanisms (Okafor 2018 [21] and Arunathanayothin 2021 [22]‡), providing a reference against which NRPD-induced changes can be evaluated, Figure 5.

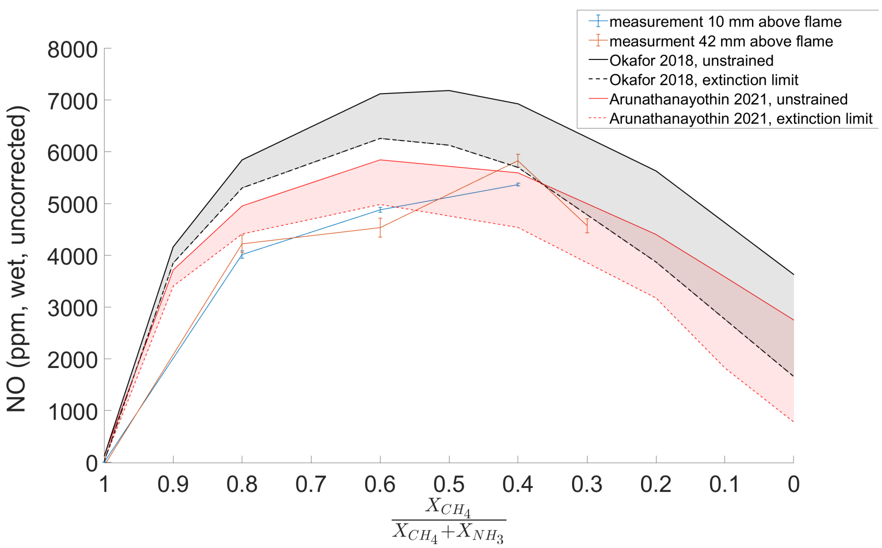


Fig. 5 Measured NO mole fraction data for ϕ = 1.0, NH_3/CH_4 blends at an air flow rate of 15 lpm for two different probe heights above the burner surface compared to two standard chemistry models. Error bars are the standard deviation of the mole fraction $\sigma/\sqrt{n}$ where n is the number of time-averaged data points from the RGA.

*The resulting lifted flame is laminar, but no longer completely flat.

†Preliminary optical emission spectroscopy, suggested that the spark mode erodes or etches the stainless steel electrodes.

‡The extinction limit shown in Figures 5 and 7 for Arunathanayothin 2021 is an estimate as we were unable to get CHEMKIN's extinction strain rate calculator to work for this mechanism.

IV. Results and Discussion

The following measurements focus on the impact of NRP discharges in the burnt gas region on NO emissions. For all cases reported, the discharge was operated in a nanosecond spark mode, with a pulse repetition frequency of 10 kHz and energy deposition around 1.0 mJ per pulse. Plasma was pulsed using a duty cycle, with a pulse train of 100 pulses on and 1900 pulses off. Air flow rate was kept constant at 15 lpm across all tests, and the flow rate of NH_3 and CH_4 was adjusted for a range of fuel blends up to 40% NH_3 for a range of equivalence ratios ($\phi = 0.8 - 1.1$) spanning rich to lean operation.

A. Configuration 1: Treatment of Exhaust Gases with NRPD

The first set of results reports on Configuration 1, as shown in Figure 1a. The distance between electrodes in this configuration was 15 mm, with the cathode sitting 30 mm from the burner surface. The RGA samples the exhaust 38 mm from the flame directly in the region of discharge generation. Results are time averaged from RGA data.

Figure 6 shows measured NO mole fraction for various equivalence ratios and NH_3/CH_4 blends, with and without plasma generated in the burnt gas region. In all cases, an increase in NO when plasma was on was observed, with leaner mixtures having the greatest increase in NO mole fraction of about 200-250 ppm penalty across blends. These experiments suggest that NRP discharges in the exhaust region of the flame consistently produce an NO penalty, however this must be investigated further for a range of combustion and electrical parameters.

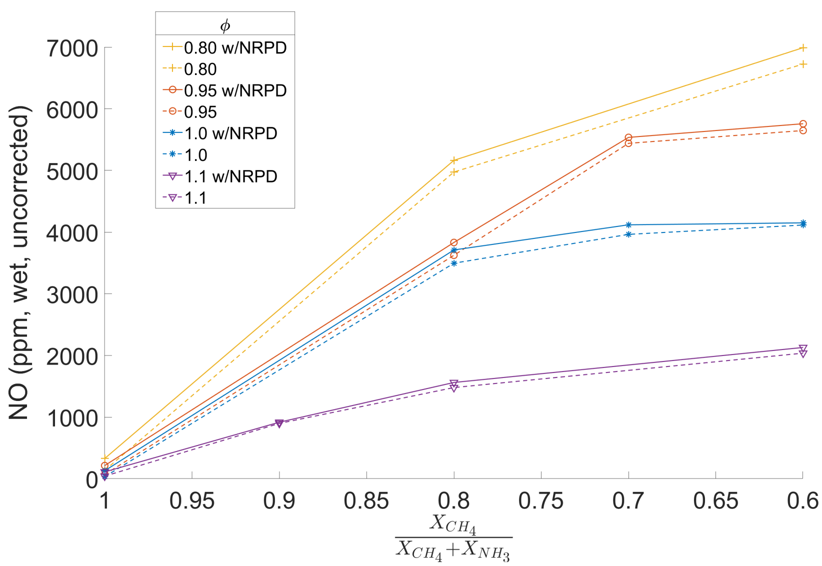


Fig. 6 Measured NO mole fraction with and without NRP discharges actuating on the burner exhaust for ϕ = 0.8, 0.95, 1.0, 1.1 for a range of NH_3/CH_4 fuel blends up to 40% NH_3. Configuration 1.

B. Configuration 2: In-situ Treatment of Flame with NRPD

These results use the alternate operation mode of Configuration 2, as explained in Section III, where the flame anchors to the grounded electrode rather than the burner. To allow the flame to anchor on the ground cathode, the plasma assembly was lowered to 9 mm from the burner surface. The distance between electrodes remained at 15 mm. The RGA sampled the exhaust 22 mm from the flame directly in the region of discharge generation. Results are time averaged from RGA data.

Figure 7 shows NO measurements for stoichiometric flames, for a range of fuel blends, using the in-situ configuration. The measured NO mole fraction increased with NRPD for all conditions, with the magnitude increases, relative to the no-plasma case, exceeding those of Configuration 1. This trend was unexpected as recent studies suggest that direct plasma interaction with the flame can be a pathway for NO consumption [7, 9, 23, 24]. Several factors may explain why our results do not show this, the foremost being that the discharge configuration actuates on both the flame and the exhaust region, leading to net NO production despite the potential for NO consumption in the reactants/flame zones. Moreover, most prior works reporting NO consumption for NH_3/CH_4/air flames with NRPD have been performed in swirl-stabilized combustors with the plasma actuating on the injection point of the reactants [7]. In these platforms, recirculation zones and enhanced mixing could be an additional route to promote NO consumption. This work did not asses applying plasma to the reactants zone upstream of the flame which could provide a pathway of NO reduction through cracking of NH_3.

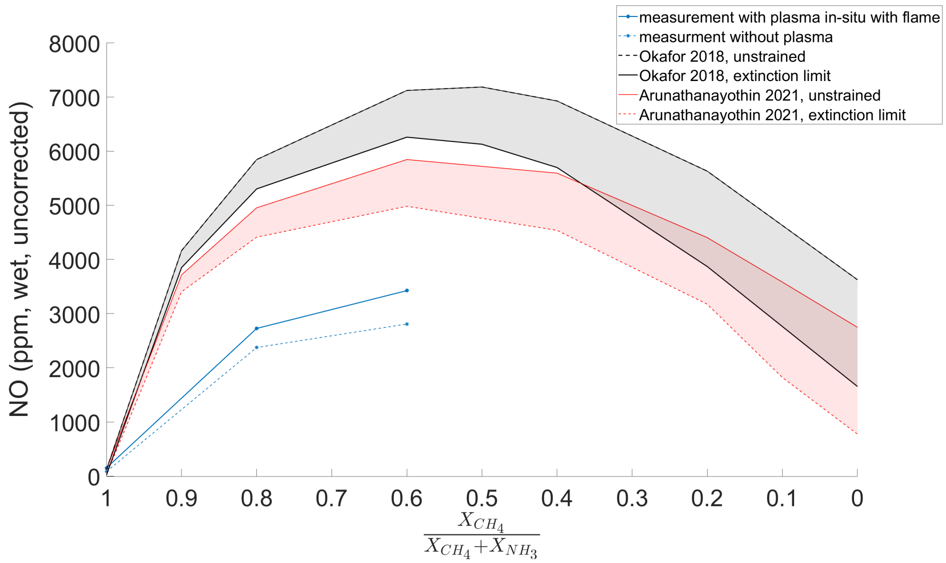


Fig. 7 Measured NO mole fraction with and without NRP discharges actuating in in-situ with the flame and on the burner exhaust for ϕ = 1.0 for a range of NH_3/CH_4 fuel blends. Configuration 2.

V. Conclusion

A modular experimental platform for plasma assisted combustion was presented to systematically investigate the effect of NRP discharges on NO emissions in elementary flames. The assembly supports both nanosecond spark and uniform discharge modes, when operating in the exhaust. Measurements of NO concentration for NH_3/CH_4 fuel blends with plasma applied in the exhaust region and within the flame are reported. An NO penalty was observed for all conditions tested, indicating that that post-flame plasma actuation is not an effective strategy for NO reduction in these mixtures. These results highlight the need for further mechanistic studies of laminar flames with NRPD and suggest that NO mitigation with plasma in ammonia flames must be approached as an optimization problem rather than assuming universal benefits. Future work will leverage this platform to perform a parametric investigation of physical and electrical parameters and develop scalable fundamental metrics that guide implementation of larger plasma assisted NH_3/CH_4/air combustors.

Acknowledgments

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