The Role of Plasma-Assisted Combustion in the Era of Decarbonization

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Abstract: Plasma-assisted combustion (PAC) enhances flame stability and aims to reduce NO_x emissions. This work uses Nanosecond Repetitively Pulsed Discharges (NRPD) to achieve clean and stable burning of ammonia and lean methane, including their mixtures. Experimental and numerical results demonstrate PAC's potential for advancing sustainable combustion in industry-relevant applications, and remaining challenges are discussed.

1. Introduction

Addressing climate change necessitates curbing CO_2 emissions, a large portion of which are generated by burning fossil fuels that constitute over 80% of the global energy production. Combustion's role in climate change is multifaceted, comprising CO_2, NO_x, CO, unburnt hydrocarbons, soot, particulate matter, and sulfate aerosols [1]. For instance, the aviation industry's climate impact triples considering nitrogen oxides and contrail cirrus, even if it contributes only 2% of total anthropogenic CO_2 emissions [1]. While electrified solutions offer decarbonization prospects, they are not feasible in sectors like long-haul transportation. Sustainable aviation fuels and hydrogen are key to decarbonizing aviation, but can still emit pollutants, notably NO_x emissions [2]. For these fuels, strategies to lower NO_x involve lean and ultra-lean mixtures, which are susceptible to combustion dynamics that may harm combustor components [4]. Ammonia, a high-density hydrogen carrier, offers potential for shipping and heavy-duty trucking but faces hurdles in combustion and NO_x emissions [3]. Hence, we need innovative technologies to stabilize flames and suppress combustion dynamics while reducing pollutants. PAC can address many of these challenges, stabilizing low-temperature flames and enhancing combustion.

For hydrocarbon flames, NRPDs have been shown to extend the lean blowout limit by up to 75% [5] and suppress thermo-acoustic instabilities [6,7]. An open question is what impact this will have on NO_x emissions reduction, as NRPDs produce NO_x, through collision of the large population of O atoms produced by the plasma, with metastable and vibrationally excited nitrogen molecules [8]. For ammonia flames, the literature is growing fast as the impact of plasma for this fuel is particularly promising. For ammonia, demonstrations on lean limit extension, by up to 35%, have been accompanied by substantial *NO_x reductions* [9]. In this presentation, we will review progress by the MIT team to address both lean burning of methane flames and stable burning of ammonia flames assisted by NRPD, with a focus on NO_x emissions reduction, and discuss persisting challenges in the field.

2. Methods

The influence of plasma on lean burn of methane and burning of ammonia is studied using simple burner configurations that allow to measure fundamental flame properties, such as the laminar flame speed [10], as well as a swirl-stabilized burner rated at 50kW [6] that addresses metrics relevant to industrial systems, such as lean blowout limit, combustion dynamics onset, and NO_x emissions. Numerical studies using a 0D model for plasma-assisted ignition (PAI) and 1D models of plasma-assisted flames are also presented and are used to evaluate the influence of NRPD on fundamental metrics like the laminar flame speed as well as emissions for NH_3 and CH_4 flames. The flamelet models, along with an energy pathways analysis tool developed in-house [11] are used to explain the macroscale observations. Enhanced actuation authority of the plasma-strategies is addressed by careful consideration of the *backward problem*, or the influence of combustion on the plasma [12].

3. Results and Discussion

Work by the MIT team has shown the ability to speed flames by up to 75% using NRPD, as well as fully suppress limit cycle combustion dynamics. We have also shown the possibility to reduce emissions in NH_3 flames [7]. Ongoing work is directed to mechanistically exploring the plasma-flame interactions, using both numerical models and a suite of experiments, to achieve repeatable and optimized outcomes, with a focus on concurrent improvement of burning and reduction of emissions.

Acknowledgement
This material is based upon work supported by the U.S. National Science Foundation (NSF), under Award Number 2339518, and by ExxonMobil.

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