NUMERICAL INVESTIGATION OF RICH-MILD-QUENCH-LEAN AMMONIA COMBUSTION IN A DUAL-STAGE BURNER WITH CYCLONIC AND QUAD JICF CONFIGURATION

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Abstract
This study explores a dual-stage ammonia/hydrogen burner using a cyclonic flow MILD burner and a Jet-In-Crossflow setup, operating under a Rich-Quench-Lean strategy. RANS and DNS simulations assess combustion performance, focusing on ammonia pyrolysis, hydrogen production, and NO_x reduction. The design proves effective in achieving stable, low-emission combustion, offering insights for sustainable fuel applications.

Introduction
The growing need for efficient and clean-burning solutions has driven the evolution of modern combustion systems. Among the various approaches, NH_3/H_2 blends have been identified as a potential alternative to hydrocarbon fuels for gas turbine engines [1]. Given the advantages of NH_3 in terms of distribution and storage over hydrogen, in many cases, it is feasible to consider generating the necessary H_2 by locally decomposing a part of the available NH_3 supply. Recent findings suggest that adopting a two-stage RQL strategy enhances flame stability and lowers emissions in NH_3-fired combustors [2,3]. In a rich-fuel operation stage, high temperatures that typically lead to significant NO_x formation are avoided, and excess NH_3 pyrolysis into H_2 is achieved. Downstream, adding secondary dilution air allows the complete combustion of the H_2 contained in the hot products stream under lean conditions, ensuring low emissions and high inlet temperatures required by turbines. The RQL strategy can be applied in a sequential combustion system [3], like Ansaldo Energia's CPSC, currently integrated into the GT36 engine. The strategy implemented in the first stages is to use classical premixed jet combustors [3]. An alternative solution is investigated in this work, where MILD combustion [4] is applied to the rich conditions of a primary-stage cyclonic burner at high pressure. Operating under rich MILD conditions, the primary stage generates incomplete combustion products and NH_3 conversion into H_2 by maintaining a low temperature of the hot products. These are subsequently burnt in a lean secondary stage that incorporates four distinct JICF arrangements for air dilution. This design enables a controlled transition from rich to lean combustion, thus resulting in optimized temperature distributions and minimized pollutant formation.

Computational strategy

In the present study, we first perform a set of RANS simulations to investigate different equivalence ratios coupling between the Laboratory Unit CYclonic (LUCY) burner geometry [5], used as the first stage (Φ = 1.05-1.3), and a square duct with four normal JICF as the second stage (Φ = 0.125-0.2), at 5 bar. The reference cyclonic consists of a prismatic chamber of 20×20×5 cm^3 with two antisymmetric pairs tubes for reactants feeding, while the gas exit is located orthogonally to the inlet jets, in the center of the chamber bottom face. Such a burner design allows for the establishment of a cyclonic flow field, ensuring the attainment of MILD combustion conditions for a wide range of operating conditions in terms of global equivalence ratio and thermal power levels. In particular, the oxidizer (air) and fuel (NH_3) injectors consist of cylindrical ducts with internal diameters of 0.8 cm and 0.15 cm, respectively. The oxidizer is preheated at 550 K, whereas the fuel is fed at ambient conditions (300 K). In the second stage, the square duct (L = 2.2 cm) exiting from LUCY is equipped with four slotted rectangular air jets (6×1.1mm) preheated at 750 K. The entire geometry model (except the LUCY inlets) is surrounded by a material of thickness 4.5 cm, density of ρ = 4300 kg/m^3, specific heat transfer coefficient of C_p = 639 J/(Kg K), and a thermal conductivity of k = 3.6 W/(m K). This material is equivalent to three different materials layered around the cyclonic burner in the experimental configuration. The numerical setup related to the first stage was validated through comparison with the experimental data available in literature at one atmosphere [5]. To assess the overall setup, a first set of RANS decoupled simulations is carried out using the commercial code ANSYS Fluent. The outlet boundary coming from the cyclonic burner serves as an inlet for the second stage simulation (see Fig.1a). Through this series of RANS simulations, the optimal equivalence ratio coupling between the first and second stages was evaluated to achieve the highest ammonia-to-hydrogen conversion and the lowest temperature of the combustion products at the exit of the first stage. The equivalence ratios chosen are Φ = 1.05 for the first stage and Φ = 0.125 for the second one.

In the second part of this study, the RANS simulation of the chosen configuration is used to initialize the flow domain for the DNS of the second stage. The DNS simulation is conducted through the HeaRT code [2]. A staggered finite-difference scheme is used to solve the compressible, reactive N-S equations, where each chemical species has its individual transport equation. Chemical reactions are modeled using the Jiang improved kinetic mechanism [6] for NO_x formation, considering NH_3 combustion at high pressure. Diffusive fluxes are calculated using a second-order accurate centered scheme, and convective terms are modeled through the $AUSM^+$-up method, coupled with a hybrid third/fifth-order accurate WENO interpolation to minimize spurious oscillations in regions of strong gradients. Extended non-reflecting boundary conditions are employed at open boundaries to consider the impact of variable transport properties and local heat release. At the air holes, synthetic turbulence equal to 5% of the average inlet speed is applied (u' = 3.36m/s). A sketch of the computational domain used in DNS is shown in Fig. 1b.

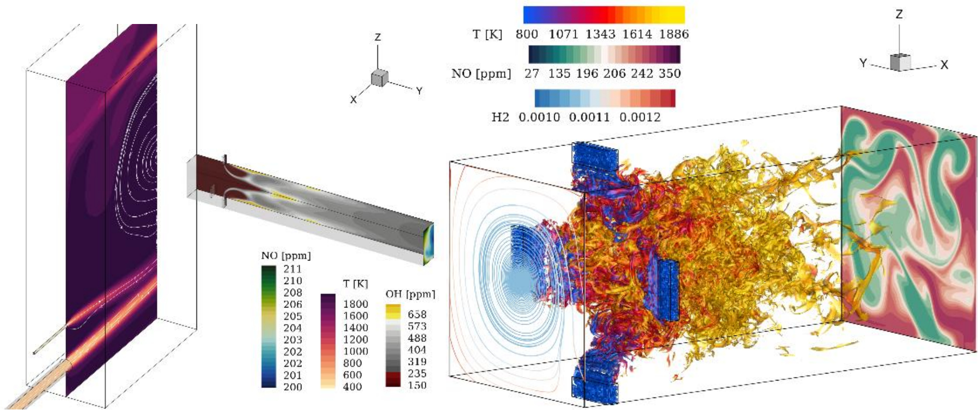

Figure 1. (a) RANS of the dual-stage burner: contours of NO at the outlet section, temperature at the middle plane of LUCY, and OH at the middle plane of the second-stage duct. Only half model is represented. (b) DNS of the second stage: iso-surface of the Q-criterion colored by the temperature, NO contour at the outlet section, and stream traces of the swirl-driven inlet, colored by H_2.

Preliminary results

The MILD first-stage burner field exhibits an organized flow structure. In Fig.1a, the velocity streamlines illustrate the interactions between the inlet jets, where the resulting swirling flow, driven by the cyclonic geometry, establishes a robust recirculation zone that enhances residence time and process stabilization. The temperature distribution within cyclonic reactor highlights a controlled thermal environment, which ensures partial decomposition of the unburnt ammonia into hydrogen, thus preparing the fuel-rich mixture for the subsequent lean second stage, while minimizing NO_x formation. In fact, at the exit of the MILD combustor first stage, hot products contain a mean concentration of unburnt $NH_3 \approx 200$ dppm and $H_2 \approx 14000$ dppm at a mean temperature of ≈1900 K. NO has a concentration of ≈150 dppm. These high-temperature gases are rapidly diluted with excess air from the second stage to completely oxidize the fuel they contain (see Fig.1b). The final temperature of these gases at the exit of the second stage is ≈1950K, while the concentration of NO is in the order of 200 dppm. The NO formation pathways analysis seems to highlight how the Zeldovich and HNO mechanisms give the greatest contribution to the formation of this pollutant.

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