Experimental investigation of instabilities during NH_3 MILD combustion in a semi-industrial scale furnace

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Abstract

An extensive experimental analysis on NH_3-air MILD combustion in a 15-kW semi-industrial furnace was performed, focused on the transition from stable to unstable regimes. The NO emissions, temperature measurements, and chemiluminescence (OH*/NH*) revealed a cup-shaped thermo-chemical oscillations that follows the same frequency evolution and shape. The temperature thresholds of this oscillatory regime were identified together with the eventual extinction temperature. Overall, this work enhances the fundamental understanding of NH_3-air MILD combustion.

Introduction

Ammonia has emerged as a promising high-density carbon-free hydrogen carrier, representing a more feasible option for transport and storage than H_2 [1]. There are significant restrictions related to its use as a fuel in practical combustion systems due to its combustion characteristics, such as low reactivity, narrow flammability limits, low flame speeds and adiabatic flame temperatures, and a tendency for high NO_x emissions. The use of innovative combustion strategies, such as Moderate or intense low-oxygen dilution (MILD) combustion has been proven to be a promising approach to overcoming the challenges related to NH_3 combustion. Sorrentino et al. [2] demonstrated that stable NH_3 combustion could be achieved in a cyclonic burner with operating temperatures above 1250 K. The authors suggested operating above 1300 K to ensure both stability and controlled pollutant emissions. Conversely, extinction occurs at lower temperatures, with the transition from burning to non-burning conditions characterized by instabilities.

The objective of this work is to identify and characterize, for the first time in a semi-industrial scale furnace, the operating conditions that trigger instabilities during NH_3-air MILD combustion.

Experimental setup and test conditions

The experiments included in this work were carried out in a semi-industrial scale reverse-flow furnace, which has been described in detail in previous studies [3]. The recuperative burner was exclusively operated in MILD combustion mode in this study at different equivalence ratios (ERs), with fuel and oxidizer injected coaxially, 8 mm and 25 mm internal diameters (ID), respectively, which ensure effective mixing of the air with the recirculated exhaust gases before it reacts with the fuel. The vertically aligned access ports on one side of the furnace are typically used to insert an air cooled suction pyrometer to perform in-situ intrusive temperature measurements, and they were also be used in this study to insert a high-response-speed (HRS) K-type thermocouple with a 0.2 mm diameter bead (db) to accurately capture the amplitude and pattern of the furnace wall temperature oscillations, when occurring. Several other K-type thermocouples (db=1 mm) were used to monitor different temperatures around the furnace and two shielded N-type thermocouples were positioned inside the combustion chamber along the central plane one on top and the other on the bottom to measure the set-point temperature (T_{sp}) of the furnace and the temperature of the exhaust gases before the heat exchanger ($T_{pre\text{-}HX}$), respectively. One of the sides of the furnace allows optical access through a quartz window. Simultaneous chemiluminescence imaging of OH* and NH* radicals were conducted using a dual-species, single-intensified CCD camera setup (La Vision). Bandpass filters were employed to capture the chemiluminescence emitted by OH* (310 ± 10 nm) and NH* (337 ± 2 nm) in the UV range. Finally, the exhaust gas composition (NO, NO_2, NH_3, O_2, and H_2O) was measured with an Emerson Rosemount CT5100 analyzer based on the Quantum Cascade Laser (QCL) spectroscopy principle. Table 1 summarizes the conditions tested for this study.

Table 1. Operating conditions tested.

Parameter	Value	Parameter	Value
Oxidizer injector ID	25 mm	Cooling air	7; 8; 9; 10 Nm^3/h
Thermal input power	15 kW	ER	0.70; 0.80; 0.90; 0.95; 1.00

Results

In the present work, NH_3-air combustion was accomplished in a semi-industrial furnace. For all the cases that were tested, the temperature was above the reference previously indicated of 1250 K. The chemiluminescence images and the intrusive temperature measurements show a well-distributed reaction, with the absence of peak temperatures as well as moderate maximum chemiluminescence intensity values.

Starting from the conditions of stable MILD NH_3 combustion, the air-cooling flow rate was gradually increased, thereby enhancing heat losses. As a result, the furnace temperature gradually decreased, allowing the assessment of how temperature variations affect the sustainability of the combustion process. The transition from stable NH_3 MILD combustion to extinction was marked by an oscillatory regime characterized by unstable periodic oscillations in temperature, emissions, and chemical species within the combustion chamber. Fig. 1 depicts the experimental temperature limits of the oxidation regimes and an example of the oscillations.

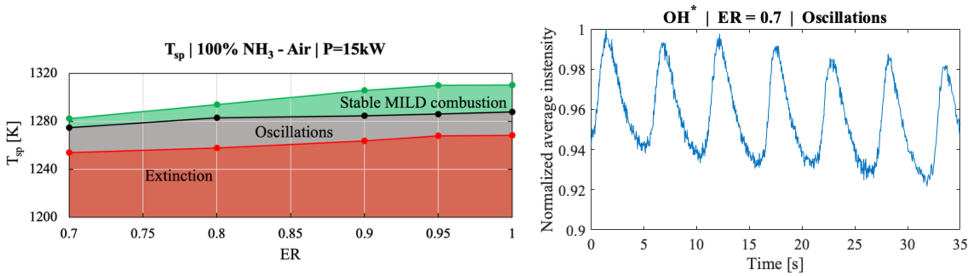

Figure 1. Limits of the oxidation regimes (left) and oscillations of OH* (right).

Temperature and chemical species data collected during the unstable regimes is characterized by high amplitude and low frequency oscillations. Based on these observations, it can be concluded that cusp-shaped thermo-chemical oscillations occur during the transition from stable NH_3 MILD combustion to extinction.

Conclusions

The transition from stable NH_3-air MILD combustion to unstable regime has been experimentally characterized in a 15-kW semi-industrial furnace. The temperature thresholds at which stable combustion transitioned into an oscillatory regime before eventual extinction were identified. These instabilities were marked by periodic fluctuations in temperature, NO emissions, and chemical species concentrations, and characterized by high amplitude and low frequency, gradually decreasing over time as NH_3 reactivity declined.

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