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Acoustic and heat release signatures for swirl assisted distributed combustion

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HIGHLIGHTS

- Examined acoustic noise and heat release fluctuations for distributed combustion.
- Distributed combustion reduced heat release fluctuations significantly.
- Oxy-fuel combustion demonstrated oscillations under unfavorable conditions.
- O_2 concentration reduction (<25%) through CO_2 addition led to stable oxy-combustion.
- Significant noise reduction achieved through distributed combustion.

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ABSTRACT

The acoustic signal and heat release fluctuations are examined from a swirl combustor using methane as the fuel. The focus was on flame stability and noise emission that have direct relevance in further developing distributed combustion for gas turbine applications and oxy-fuel combustion. Three regimes are examined in this paper, the first being a swirl mode at equivalence ratios between 0.9 and 0.55. The second one being distributed combustion, achieved through N_2/CO_2 dilution to reach oxygen concentration below 15%, fostering distributed reaction. The third was oxy-fuel flame using increased amounts of CO_2 dilution to reach distributed reaction. For the first case, lowering the equivalence ratio led to a reduction in the peak sound pressure level around 500 Hz and a decrease in heat release fluctuations. For all the equivalence ratios, close coupling between acoustic signature and heat release fluctuations existed around 200 Hz. Distributed combustion, achieved at oxygen concentration below 15%, showed a much lower peak sound pressure levels at the 500 Hz range with no coupling between heat release fluctuations and acoustic signal, outlining the flame stability at this regime. Also, the noise emission levels were significantly reduced under this mode. For the third regime, increase in CO_2 dilution resulted in high heat release fluctuations and an unstable flame which oscillated between two different flame modes, a feature that did not exist in the first two regimes. Further increase in CO_2 led to achieving distributed reaction and a much more stable flame as compared to its oscillatory behavior at lower CO_2 amounts, along with reduced noise emission levels. This outlines the possibility of achieving distributed combustion in a stable manner via CO_2 dilution in oxy-fuel flames.

1. Introduction

The quest for environmentally friendly energy conversion as well as increased awareness of greenhouse gas (CO_2) emission and its impact on climate change and global warming have motivated energy researchers to look for advanced methods to utilize available fossil fuels. In almost all cases the objectives are minimizing the pollutants emitted during energy conversion and also limit the amounts of carbon dioxide (CO_2) emitted to the atmosphere. Over the past couple of decades, different research groups have proposed combustion methods that minimize combustion emissions, such as rich-quench-lean burn (RQL) [1–3], flameless oxidation (FLOX) [4,5], moderate or intense low oxygen dilution (MILD) [6], and colorless distributed combustion (CDC) [7,8].

Carbon capture and sequestration has been proposed and demonstrated to mitigate the greenhouse gas emissions so that one can continue using available fossil fuels while mitigating the harmful effect of carbon dioxide emission. To alleviate the process of separating CO_2 from the product gases stream (which contains

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large amounts of nitrogen due to air combustion), oxy-fuel combustion has been proposed and demonstrated. The benefit of oxy-fuel combustion is that the product gases are mainly CO_2 and water vapor, making the separation process much easier with significant and cost savings and increased plant efficiency. The benefits of oxy-fuel combustion include ease of carbon dioxide separation, and mitigation of thermal and prompt NO_x formation due to no nitrogen in the oxidizer. It is noteworthy that most of the NO_x formed in gaseous fuels combustion is from thermal NO_x route following the Zeldovich mechanism [9].

Dynamic stability of flames, and their response to fluctuations is one of the critical factors in clean combustion. It is critical to ensure that any momentary fluctuation in the inlet flow does not create significant perturbations to the heat release from within the combustor that can feed back to the initial fluctuations via dynamic pressure oscillations. Such feedback can create resonance, flame extinction, as well as undesired damage to the combustor body and injectors as well as increased noise emission levels. The dynamic response of flames and flame transfer function (relation between heat release fluctuations and inlet flow fluctuations) have been studied in details to understand the controlling factors behind this behavior for different combustors [10–14]. Other researchers focused on the underlying reasons of such instabilities with extension to lab scale flames [15–17] and swirl flames [18–20], offering significant insights on these instabilities and the associated impacts from them.

As the importance of flame instabilities and flame dynamic response is established, this paper focuses on examining a swirl flame burner with special emphasis on its transition to colorless distributed combustion mode using both air combustion and oxy-fuel combustion. Colorless distributed combustion relies on the internal recirculation and entrainment of reactive hot species and product gases from within the combustor, and their fast mixing with the fresh mixture to form a low oxygen concentration and high temperature mixture prior to ignition. The low oxygen concentration slows down the reaction rate such that the reaction covers a larger volume to result in distributed reactions with the same fuel consumption. This low reaction rate is maintained by the high temperature of the oxidizer. Under this conditions, the reaction rate is uniform across the reactor volume to alleviate any hot spots and/or any local stoichiometry variation. CDC investigations have demonstrated significant emissions reduction under different configurations [7,8,21,22] and fuel flexibility [23,24]. The required conditions to achieve CDC and the subsequent uniform local equivalence ratio and thermal fields within the reaction zone has been described in the literature; distinguishing distributed combustion from swirl assisted flames under the same flow conditions [25,26]. However, to date, there has been no effort to quantify any fluctuations in the flame as there were no noticeable instabilities under distributed combustion condition. One of the goals of this paper is to fill this gap.

Though no instabilities have been observed while transitioning to distributed combustion using N_2/CO_2 dilution, the same cannot be said for oxy-fuel combustion with CO_2 dilution to achieve distributed combustion. This is owing to oxy-fuel combustion characteristics being different than that of air combustion in several aspects. Oxy-fuel combustion is characterized by higher flame speed (up to an order of magnitude larger [27]). In addition, higher adiabatic flames (by ~30%) are another aspect of oxy-fuel combustion. These two features dictate that large amounts of exhaust gases are needed (using for example recirculation) to result in decreased flame temperatures, thus preventing excessive heat evolution and to stabilize the flame [27,28]. Oxy-fuel combustion has been studied in details with focus on furnace applications [29–33]. Some studies have suggested that the flame is difficult to stabilize below 21% oxygen concentration in oxygen-carbon dioxide mixtures [34,35].

In this paper, the flame acoustic signature and heat release fluctuations are quantified under different conditions representing swirl flames, transition to distributed combustion using N_2/CO_2 dilution, and oxy-fuel combustion with increased CO_2 dilution. To identify heat release fluctuations, CH* chemiluminescence diagnostics was used as CH* has been widely reported to be one of the markers for flame, especially when evaluating flame transfer function [36–39]. As for the acoustic signatures, calibrated microphones were used as described in the next section. Identifying both signals (acoustic and heat release fluctuations) are critical to assess the flame behavior and stability under distributed combustion as well as the possibility of incorporating distributed combustion with oxy-fuel operation.

2. Experimental facility

The experiments were performed using a swirl burner fueled with methane in three different combinations for oxidants (methane-air, air-methane with N_2/CO_2 dilution, and oxygen-methane with CO_2 dilution), see Fig. 1. Details of this swirl burner can be found elsewhere [25]. To simulate product gas entrainment and lower oxygen concentration in the mixture prior to ignition, different amounts of N_2-CO_2 mixture were added to the air upstream of the burner. The flow control setup can be found in the literature along with measurement accuracy on data [25]. Nitrogen and carbon dioxide were mixed in a ratio of 90% N_2-10% CO_2 by volume simulating product gases near stoichiometric conditions. Further details on this selection can be found in the literature [25]. The flow field for this swirler has been characterized under both reacting and non-reacting flow relating to the cases studied herein. In these investigations, the mean and fluctuating velocities were obtained along with the reaction zone with focus on fluid mechanics behavior and flame-flow interaction [40–42].

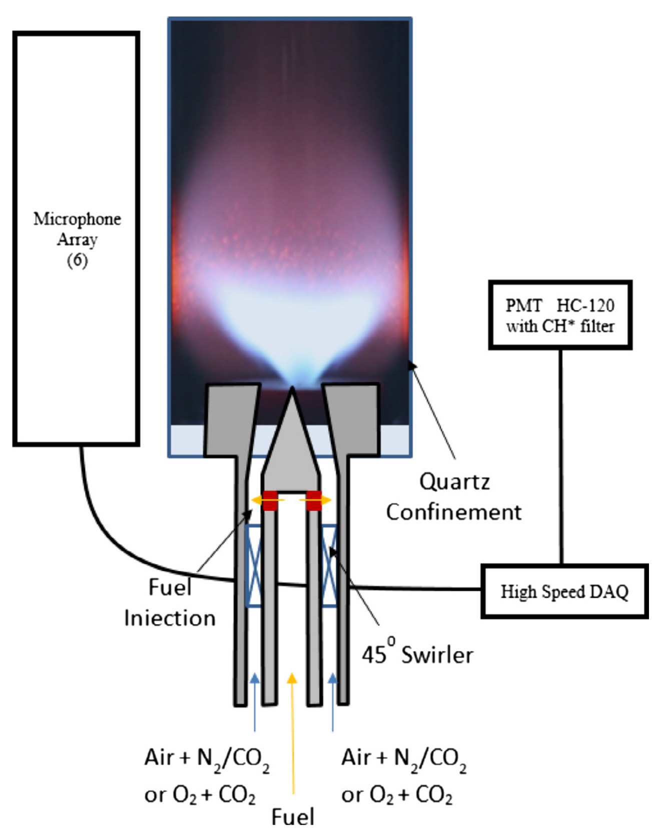

Fig. 1. Schematic of the experimental test rig.