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Thermal field investigation under distributed combustion conditions

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HIGHLIGHTS

- Examined the thermal field behavior under conventional and distributed combustion.
- N_2 and CO_2 are used to simulate entrained combustion gases from within the combustor.
- Reduced oxygen concentration (<15%) is key to achieve thermal field uniformity.
- Distributed combustion reduced temperature variation by 50% axially & 60% radially.
- Significant noise and emissions reduction was achieved via distributed combustion.

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ABSTRACT

Distributed combustion has demonstrated significant performance gains, especially on combustion efficiency and near zero pollutants emission. Controlled mixture preparation between air, fuel and internal hot reactive gases prior to mixture ignition is a critical requirement to achieve distributed combustion condition. Though distributed combustion have been extensively studied using a variety of geometries, heat loads and intensities, and fuels, limited information is available on the role of hot reactive gas entrainment and the resultant thermal field uniformity. In this paper, the impact of internal entrainment of hot reactive gases on thermal field uniformity and pollutants emission is investigated. A mixture of nitrogen and carbon dioxide was introduced to the fresh air stream prior to mixing with the fuel and its subsequent combustion to simulate the product gases from within the combustor. Increase in the amounts of nitrogen and carbon dioxide (simulating increased entrainment) significantly reduced pollutants emission, enhanced thermal field uniformity, and increased the reaction volume to occupy larger portion of the combustor. This was evident through spatial temperature measurements in the combustor along with the enhanced distribution of the flame visible signature and OH* chemiluminescence signal. The temperature data demonstrated that lowering oxygen concentration from 21% to 15%, through increased entrainment, promoted distributed combustion conditions with lower overall temperature rise throughout the combustor. In addition, the peak temperature regions associated with swirl burners disappeared, eliminating most of the hot spots in the combustor. The enhanced thermal field uniformity and reduced temperature variation provided ultra-low emissions, demonstrating the impact of enhanced thermal flowfield uniformity on emissions. Experiments performed at different equivalence ratios and entrained gas temperatures demonstrated similar behavior of thermal field uniformity and ultra-low emissions.

1. Introduction

The increase in fossil fuels as a local energy source to satisfy the states' energy needs, along with concerns about global warming and climate change, have motivated combustion researchers to develop new combustion methods that has minimal impact on the environment and high efficiency. The potential for natural gas and shale gas deployment in electricity and power generation have been fostered by their increased availability as a local energy source and their lower carbon emission (compared to other fossil fuels such as coal). To ensure this mandated environmentally friendly performance, future combustion systems shall achieve even lower pollutants (including NO_x, CO, unburned hydrocarbons and soot) while minimizing CO_2 emissions. To this end, distributed combustion (Colorless Distributed Combustion, CDC [1–4]), among other technologies (i.e., FLOX, MILD) [5–7], has been shown to provide significant benefits of reducing the emissions of NO and CO along with stable combustion, reduced noise, no flame fluctuations and combustion instability. CDC combustors have also

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demonstrated fuel flexibility, handling a variety of liquid and gaseous fuels with no modification to the combustor [8]. The flames in distributed combustion do not show any visible flame signatures so that the flame so formed is termed colorless due to negligible visible emission as compared to conventional flames.

The performance benefits of CDC have been demonstrated using a variety of geometrical arrangement for the combustor flowfield, air, and fuel injection schemes [9–12]. The focus in these investigations was on the internal entrainment of hot reactive species and gases and their subsequent mixing with the freshly introduced air and fuel. This entrainment and the subsequent adequate mixing prior to ignition forms pivotal step in achieving distributed reactions. Distributed reactions are characterized by a lower reaction rate over the entire volume of the combustor, as opposed to the concentrated flame front characterized by high reaction rates with local hot spots, to result in the same fuel consumption with lower temperature rise in the combustor. This low reaction rate is achieved through lowering the oxygen concentration in the reactants, and increasing the temperature of the reactants (both achieved simultaneously through the entrainment of hot reactive gases from within the combustor). The distributed combustion regime not only avoids the formation of thin reaction zone but also the hot-spot zones in the flame, which help mitigate thermal NO_x formation and emission from the Zeldovich thermal mechanism [13,14].

The impact of the amount of gas entrainment and recirculation on reaction distribution and pollutants emission have been investigated with focus on determining the minimum entrainment requirements for distributed reactions to occur (hot gas recirculation/oxygen concentration) [15]. In these investigations, a swirl burner was used with focus on determining emissions (NO and CO) and flame behavior (radicals' chemiluminescence signal) with different amounts of recirculation. A mixture of nitrogen and carbon dioxide (90–10% by volume) is used to simulate the product gases.

These investigations showed that reaction distribution is significantly enhanced with increased entrainment, lowering oxygen concentration in the ready-to-ignite mixture. This reaction distribution was fostered at oxygen concentration below 15%, to result in ultra-low emissions. However, limited information is available on the thermal field uniformity within the reaction zone.

Swirl burners thermal field have been studied in details with focus on mean and fluctuating temperatures. Hedman and Warren [16] have used coherent anti-Stokes Raman spectroscopy (CARS) to measure temperature in a dual swirl combustor, where they showed that the temperature increases across the centerline then decreases near the exit, with significant radial change across the swirl boundary. Similar behavior was also shown by Keck et al. [17]. Cheng et al. [18] used *R*-type thermocouples showing the same radial temperature change across the swirl stabilized combustor. The temperature profile has also been numerically examined [19,20] with similar behavior as those measured experimentally.

In this paper, the thermal field uniformity is evaluated from the temperature measurement throughout the reaction field under distributed combustion conditions. Comparison between the temperature values under distributed reaction conditions and normal combustion will aim to outline the significant thermal field uniformity expected under distributed combustion condition. Various conditions will be examined to identify the cause of this field uniformity and its direct impact. These conditions include variations of stoichiometry, heat load, and different diluents temperature.

Nitrogen and carbon dioxide were selected as they represent majority of the product gases. They were mixed in a 90% N_2–10% CO_2 by volume simulating product gases near stoichiometry conditions. It is recognized that this ratio changes as the equivalence ratio becomes leaner, the diluting gases mixture (90–10%) was kept constant. Any minor deviation from the actual composition will have minimal impact on the results as nitrogen and carbon dioxide behave similarly in flames. Laminar flame speed and flame temperature for methane-air flames diluted with nitrogen and/or carbon dioxide have shown to exhibit similar behavior [21,22]. Diluting the reactants with a nitrogen–carbon dioxide–water vapor mixture also resulted in similar behavior to that of nitrogen [23].

2. Experimental facility

The experiments were performed using a swirl burner fueled with methane. Details of this swirl burner can be found elsewhere [24]. The performance of this swirl burner has been studied in terms of emissions and velocity profiles using methane and hydrogen enriched methane [24,25]. To simulate product gas entrainment and recirculation, and reduce 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. Fuel was injected at the center of the swirler in a non-premixed configuration. Air and nitrogen flowrates were controlled by laminar flow controllers with an accuracy of ±0.8% of reading and ±0.2% of full scale leading to an overall accuracy of 1.5% of the reading. Methane and carbon dioxide flowrates were controlled through gravimetric flow controllers with an accuracy of 1.5% of full scale.

Detailed temperature measurements were performed using a K-type thermocouple with NI-DAQ (data acquisition) system calibrated using blackbody calibrator (Omega BB-4A) resulting in an accuracy of ±3%. This accuracy is established based on the maximum difference between the thermocouple reading and the reference thermocouple in the calibrator. The thermocouple was mounted on a traverse mechanism to allow measurement at different axial and radial positions from within the flames. The thermocouple was continuously sampled with the mean of 50 readings reported herein as the average temperature. An ICCD (Intensified Charge-Coupled Device) camera coupled to a narrow band filter for OH^* chemiluminescence detection (UV interference filter centered at 307 nm with a FWHM of ±10 nm) was used to evaluate the flame behavior upon the insertion of the thermocouple into the combustor. It is imperative to ensure that the flame characteristic do not change upon the movement of the thermocouple. This is especially critical under distributed combustion conditions where the flame might anchor on the thermocouple.

For pollutants emission, the products of combustion were continuously sampled at the exit of the burner. The concentration of NO was measured using a NO–NO_x chemiluminescent gas analyzer, CO concentration was measured using the non-dispersive infrared method and O_2 concentration (used to correct the NO and CO emissions at standard 15% oxygen concentration) was measured using galvanic cell method. During a single experiment, measurements were repeated at least three times for each configuration and the uncertainty was estimated to be about ±0.5 ppm for NO and ±10% for CO emission. The experiments were repeated at least three times to ensure good repeatability of the experimental data obtained.

The experimental rig is shown in Fig. 1 with the flame at two different conditions of normal air combustion wherein the swirl structure is dominant (left photo), and reduced oxygen concentration combustion showing near distributed combustion with less visible emission (right photo).

3. Experimental investigations

Table 1 summarizes the conditions for the specific experimental conditions reported here along with the variables manipulated for each case. For each heat load, the fuel flow rate was kept constant