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Full Length Article

On the flame–flow interaction under distributed combustion conditions

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HIGHLIGHTS

- Investigated flame–flow interaction in swirl and distributed combustion flames.
- Investigated the impact of dilution on flowfield with focus on O_2 Conc.
- Characterized swirl flames and distributed combustion using OH-PLIF.
- OH-PLIF and velocity field assists to explore key features of distributed combustion.
- Flame–flowfield interaction unravels why low emission from distributed combustion.

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ABSTRACT

Colorless Distributed Combustion (CDC) has shown simultaneous benefits of high combustion efficiency, ultra-low pollutants emission, low combustion noise, uniform thermal field, and enhanced stability. Distributed combustion is fostered by reduced oxygen concentration and high temperature oxidizer to result in distributed reaction over a larger volume of the combustor and uniform thermal field. In this paper, the interaction between the velocity field (characterized through Particle Image Velocimetry) and the reaction region (identified through hydroxyl Planar Laser Induced Fluorescence) is investigated with focus on swirl assisted distributed combustion. A mixture of nitrogen and carbon dioxide was mixed with normal air upstream of the burner to simulate the hot reactive gases. The flowfield was characterized under non-reacting conditions to outline the impact of the added dilution on the flowfield. The results showed dilution to enhance both the inner recirculation and outer recirculation zones. Reacting flowfield, characterized to determine the impact of the temperature rise and density changes, showed maximum velocity region to shift downstream. Comparing the PIV data for reacting conditions with OH-PLIF revealed significant difference between normal swirl and CDC flames. In swirl flame, the flame was located around the shear layer of the entry jet (with both the inner and outer recirculation zones) where the velocity fluctuations and OH-PLIF fluctuations coincided. Flame transitioning to CDC pushed the reaction zone further downstream to locate at a position of lower velocity than what was found for swirl flames. In addition, the reaction zone occupied a much larger volume with lower signal intensity to exhibit distributed reaction. Experiments performed at same flow rates and velocities but with no reduction in oxygen concentration confirmed that the change in reaction behavior is attributed to the lower oxygen concentration rather than the increased flowrates due to dilution.

1. Introduction

Colorless distributed combustion (CDC) offers most promise for near zero emission to conform to increasingly stringent pollutants emission regulation. The performance of CDC has been investigated over a wide variety of geometries, heat release intensities, and fuels [1–5]. CDC shares some of the basic principles of high temperature air combustion (HiTAC) that has demonstrated ultra-low emissions, uniform thermal field, and significant energy gains for atmospheric pressure furnace applications [6]. In HiTAC, low oxygen concentration air, preheated to high temperatures, is used for combustion. The temperature of combustion gases in the furnace is some 50–100 °C higher than that of the preheated low oxygen concentration fuel-air mixture just prior to ignition. The low oxygen concentration in the incoming reactants (only about 2–5% by volume) can be achieved, among other methods, through the internal (or external) recirculation of combustion gases, which also increases the air temperature [6]. In CDC, decrease in oxygen concentration and increase in temperature of

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the fresh mixture stream is achieved through internal entrainment of hot reactive species from within the combustor. This entrainment and the subsequent adequate mixing prior to ignition are critical components to achieve distributed combustion. Distributed combustion is characterized by volume-distributed reaction over the entire volume of the combustor as opposed to thin concentrated flame front characterized by high reaction rates and presence of local hot spots in normal combustion, 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 of the reactants, and increasing temperature of the reactants (both of which can be achieved through entrainment of hot reactive gases). The distributed combustion regime avoids not only the formation of thin reaction zone but also the hot spot zones in the flame. This helps to mitigate thermal NO_x formation and emission from the Zeldovich thermal mechanism [7]. The overall temperature of the flame is low so that there is no need to dilute the hot gases before introducing them to the turbine. This reduces power requirements of the gas turbine's compressor to directly enhance the gas turbine efficiency and simultaneously enhance both combustor and turbine lifetime.

Other technologies have also emerged with focus on addressing pollutants emissions with relevance to gas turbines combustion. These technologies include flameless oxidation (FLOX) [8,9] and moderate or intense low-oxygen dilution (MILD) [10]. However, these technologies have similar goals, the approach and performance is different from CDC.

For all the aforementioned investigations involving CDC, the entrainment of hot reactive gases from within the combustor have resulted in lower emissions and enhanced thermal field uniformity in the combustion chamber. This has been shown through changing the geometry/injection velocity and measuring the entrainment (through PIV) and coupling that with the resultant pollutants emission [4,11]. Though these investigations have offered much insight on the role of entrainment, critical questions remain concerning the amounts of entrainment required to achieve distributed combustion.

The critical entrainment amount was investigated in a swirl burner with focus on determining the amounts of oxygen concentration at which volume distributed reaction occurs [12]. The swirl burner allowed for good optical access for laser diagnostics. This work [12] showed that distributed reaction occurs at an oxygen concentration of about 15% with the reactants introduced at room temperature. This investigation revealed that the reduction in emission is from oxygen concentration reduction rather than dilution of the gases. This was confirmed by performing experiments with no dilution, increased air and fuel flow rates, air dilution (lower equivalence ratio) and N_2–CO_2 dilution (lower oxygen concentration) conditions [13]. Reynold's number was kept constant for the latter three investigations to eliminate velocity change effects. Lowering oxygen concentration demonstrated lower emission as compared to adding more air or increasing air and fuel amounts to increase overall velocity. In addition, distributed combustion was only evident in lower oxygen concentration cases while the other cases demonstrated the traditional swirl flame structure as evidenced from the OH^* chemiluminescence images shown in Fig. 1. Thermal field investigation also showed that the thermal field under distributed combustion is substantially different from that of a swirl flame. The temperature variation was negligible with a uniform temperature distribution [13].

In this paper, the velocity flowfield under swirl flames and distributed combustion conditions is investigated with focus to extract the main flow features. The flowfield measurements are coupled with hydroxyl (OH) planar laser induced fluorescence to determine the interaction between the flowfield and the reaction zone. OH-PLIF is picked over OH^* chemiluminescence as it offers both average and instantaneous measurements over a thin plain (laser sheet thickness). On the other hand, OH^* chemiluminescence is a line of sight method. Though Abel transform (Abel inversion) has been successfully applied to axisymmetric flames, as the flame transformed to distributed combustion, the inversion results were unsatisfactory. Several researchers have combined velocity field and OH-PLIF (mean and instantaneous) data to study the behavior of swirl flames and jet flames in details [14–19], resulting in useful insights. Comparing the velocity field and OH-PLIF field under swirl flames and distributed combustion conditions provides the main differences between them to help explain the flame characteristics under each case. The details of the experimental facility and the laser diagnostics are given next.

2. Experimental facility

The experiments were performed using a swirl burner with a 45° swirl angle. Details of the swirl burner can be found elsewhere [20]. A mixture of 90% nitrogen 10% carbon dioxide was used to simulate entrained product gases. Laminar flow controllers with an accuracy of ±0.8% of reading and ±0.2% of full scale were used to control the air and nitrogen flow rates, leading to an overall accuracy of about 1.5% of the reading. Methane and carbon dioxide flow rates were controlled through gravimetric flow controllers with an accuracy of 1.5% of full scale. Fuel (methane) was injected at the center of the swirler in a non-premixed configuration. Fig. 2 shows the flow configuration of the swirl while Fig. 3 shows a schematic diagram of the facility and the diagnostic tools.

2.1. Particle image velocimetry

For measuring velocities, a particle image velocimetry (PIV) system was used. The camera was located at a distance of 0.5 m away from the laser plane. The camera view covered an area of 8.4 cm × 6.3 cm. Portion of the air supplied to the combustor was diverted to a fluidized bed seeder, where the seeding particles were picked up by the air and then combined with the main line as shown in Fig. 3. The portion of air diverted was about 10% and the flow rates of the main air and seeding air were controlled to reach the desired total air flow for all the experimental conditions examined. The seeding particles used were Alumina with a nominal particle diameter of 2 μm. The laser sheet beam had a thickness of about 1 mm. Table 1 summarizes the different parameters of the PIV system. For data processing, PIVLab was used [21]. For each data set, four passes were performed with interrogation window size of 64, 32, 16, and 8 pixels with 50% overlap. The interrogation window size was selected such that the maximum displacement was less than third of the window size. High reflection regions and noise were handled through masks to eliminate erroneous vectors resulting from the high signals, leading to areas of "no vectors" in the velocity field. The PIVLab output was further processed in Matlab to obtain mean and fluctuating velocities and other relevant quantities. The estimated error in the PIV experiments based on particles used (material and size) as well as velocity gradients were less than 15% [22].

2.2. Planar laser induced fluorescence

The excitation of OH radicals requires activation through a specific laser wavelength. This is achieved through a dye laser system with a UVT (Ultraviolet Tracking) unit with active wavelength control to eliminate laser line "walking" (drop in power). The dye laser system consists of a pump laser (Continuum PL9000) used to excite "pump" the dye, a dye laser unit (ND6000), where Rhodamine 590 dye is circulated and exposed to the pump laser.