Internal Entrainment Effects on High Intensity Distributed Combustion Using Non-Intrusive Diagnostics

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Abstract

High intensity colorless distributed combustion (CDC) provides high efficiency combustion with stable operation and ultra-low emissions. The role of internal entrainment of hot reactive gases requires further investigation in order to obtain minimum requirements for distributed combustion. In this paper, the impact of internal entrainment of reactive gases on the flame behavior and structure is investigated with focus on fostering distributed combustion. A mixture of nitrogen and carbon dioxide was introduced to the air stream prior to mixing with the fuel to simulate the recirculated product gases from within the combustor. Increase dilution with nitrogen or carbon dioxide increased the reaction zone volume to result in uniform distribution of CH* and OH* chemiluminescence signal and uniform equivalence ratio (measured optically). These conditions replaced the normally present blue flame with a uniform almost invisible faint bluish flame. The increased entrainment also decreased NO chemiluminescence significantly for the same amounts of fuel burned. The chemiluminescence data suggested that lowering oxygen concentration from 21% to 15% resulted in improved distributed combustion conditions with the reaction volume occupying most of the combustor. These conditions provide the minimum entrainment requirement and reduction of oxygen concentration for achieving distributed combustion. Results obtained at different equivalence ratios and entrained gas temperatures showed similar behavior at oxygen concentration of 15%. The reaction distribution was further enhanced at lower oxygen concentration (~11%) with further reduction in pollutants emissions.

Keywords: High intensity distributed combustion, Gas turbine combustion, Local equivalence ratio, Reactive gas entrainment, Ultra low NO_x.

1. Introduction

Increasing energy needs, with rising concerns about global warming and climate change, have motivated researchers to develop new methods of energy conversion using available energy sources with minimal impact on the environment. From these sources, natural gas and shale gas

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provide themselves as low carbon energy sources that can be converted to usable energy through combustion with minimal environmental impact (as compared to other fossil fuel). The potential for these gases for electricity and power generation have been fostered by their increased availability as a local energy source. The combustion systems developed for natural gas need to comply with the stringent emissions regulation to form a pivotal part of the quest for environmentally friendly energy systems. To ensure environmentally friendly performance, these combustion systems shall achieve near zero emission of pollutants (such as, NO_x , CO, unburned hydrocarbons and soot) while minimizing CO_2 emissions. To this end, colorless distributed combustion (CDC) has been shown to provide the benefits of reducing the emissions of NO and CO, and improved pattern factor with enhanced thermal field uniformity in the entire combustor [1-3]. Stable combustion with reduced noise and no flame fluctuations have also been shown for CDC conditions along with fuel flexibility [4] and enhanced thermal field uniformity [5]. 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 gains from CDC have been demonstrated using different geometrical arrangement for the combustor flowfield, air injection, and fuel injection [6-9]. These geometries and injection scenarios were examined with focus on enhancing the entrainment of hot reactive gaseous species from within the combustor and their subsequent mixing with the freshly introduced air and fuel. This entrainment and the subsequent adequate mixing prior to ignition are critical components to achieve 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

60 consumption with lower temperature rise in the combustor. This low reaction rate is achieved through lowering the oxygen concentration in the reactants, and maintained by the increased temperature of the reactants (both achieved simultaneously through the entrainment of hot reactive gases). The distributed combustion regime not only avoids the formation of thin reaction zone but also the hot-spots in the flame that help mitigate thermal NO_x formation and emission
65 from the Zeldovich thermal mechanism [10, 11].

For all the aforementioned investigations, increased entrainment of hot reactive gases from within the combustor decreased emissions and enhanced thermal field uniformity in the combustion chamber; however, critical questions concerning the minimum required amount of entrainment remains unaddressed. Increasing the entrainment of hot reactive gases and their
70 mixing with the fresh reactants lowers the oxygen concentration in the overall mixture and increases the mixture temperature, but no information is available on the required oxygen concentration to achieve distributed reactions. Previous results have provided the basic requirements on conditions (such as, oxygen concentration and temperature) to achieve distributed reactions in furnaces [11, 12], which are characterized by lower thermal intensity and
75 near stoichiometric combustion. It was concluded that oxygen concentration of about 8% or lower results in no color (colorless) to the flame. Other researchers have shown that the reaction is more distributed at 4% oxygen concentration as compared to 21% oxygen in air. This was demonstrated with and without air preheats prior to combustion [13]. However, these two studies focused on low intensity combustion characteristic of furnaces rather than the present efforts on
80 high intensity gas turbines.

For gas turbine combustors, 40% reduction in NO_x has been demonstrated with 35% exhaust gas recirculation (EGR), leading to an oxygen concentration of 17% [14]. Other researchers have

reached similar performance gains with up to 30% EGR [15]; however, there is limited information on reaction behavior at lower oxygen concentrations as stable operation was not maintained with further increase in EGR amounts [14, 15].

The impact of entrainment on pollutants emission and reaction distribution has been studied with focus on achieving distributed reaction [16]. Different amounts of N_2 - CO_2 mixture simulating product gases were added to the fresh mixture at different temperatures for diluting the fresh mixture and lowering its oxygen concentration to simulate recirculation of hot product gases from within the combustor to achieve distributed combustion conditions. It was concluded that oxygen reduction of 3% (down to 18%) resulted in about 60% reduction in NO emission, and 75% reduction of NO emission with further reduction of oxygen concentration by 2% (down to 16% O_2 in mixture), outlining the significant impact of oxygen concentration on the behavior of the mixture and the resulting emissions [16]. This investigation focused on only the final outcome in terms of pollutants emission. In this paper, the flame characteristics and shape are examined for different amounts of gas entrainment in an effort to understand the difference in flame behavior and reaction progression under distributed reaction condition as compared to normal flames. A swirl burner was used in this investigation with focus on detecting different flame light emissions and chemiluminescence.

2. Approach

To evaluate the flame characteristics with different amounts of entrainment, light emission spectroscopy was used as the diagnostic tool to examine the presence of different radicals. Excited radicals emission has been extensively used to determine the extent of reaction

distribution under different conditions. The use of selected radicals provided insights on the local equivalence ratio.

2.1. *Equivalence Ratio*

The first characteristic quantified here is the equivalence ratio and its variation with the reaction distribution. Since the chemiluminescence intensities relate to the species produced during the reaction process, the intensity of light produced (or the signal captured) is related to the rate of production/depletion of each species. These rates vary with reaction progression and is a function of equivalence ratio. Consequently, one can deduce the equivalence ratio from the chemiluminescence intensities. Numerous researchers have shown that the ratios of chemiluminescence from different radicals, such as OH^*/CH^* and C_2^*/OH^* , vary with equivalence ratio in simple flames [17-24] including liquid fueled flames [25]. In all these investigations, a similar trend was shown where the OH^*/CH^* ratio was shown to increase significantly for lean equivalence ratios.

Several researchers have focused their efforts on developing this method for equivalence ratio measurements in a swirl combustor relating to gas turbine applications with focus on lean combustion. Muruganandam et al. [26] have shown that the CH^*/OH^* signal ratio for turbulent jet flame, swirl dump combustor, and gas turbine simulator exhibit the same trend and similar value for equivalence ratios between 0.65 and 0.95. Other researches have reached similar conclusions on the trend of CH^*/OH^* ratio (or OH^*/CH^*) in swirl burners [27-29]. Muruganandam et al. [28] have shown that the CH^*/OH^* ratio remains almost the same for Reynolds numbers in the range of 11700 and 23300. They also showed that their swirl combustor data agrees favorably well with high pressure premixed laminar flame results [18]. Guyot and Lacarelle [29] measured the CH^*/OH^* ratio for Alstom EV-10 burner. They concluded that this ratio depends

exponentially on the equivalence ratio and is independent of the air mass flow. They noted that the contribution of broadband CO_2^* chemiluminescence in the wavelength range of CH^* chemiluminescence must be accounted for. Similar concerns were raised concerning CO_2^* chemiluminescence. Muruganandam et al. [28] noted that the trend can be different if no background correction is performed to account for CO_2 chemiluminescence. An example of this is the work of Docquier et al. [30], where the data trend is different than that recorded with background correction [28, 18], outlining the importance of CH^* signal correction to account for CO_2 chemiluminescence and any other background noise.

2.2. NO^* Chemiluminescence

Nitric oxides formation is one of the major issues in gas turbines combustion with ongoing focus on how to minimize or eliminate these emissions. Thermal field uniformity and low temperature rise remains the main issue to tackle thermal NO_x formation through the Zeldovich NO_x formation mechanism. In-situ NO detection have been performed using planar laser induced fluorescence (NO-PLIF) [31-34]. For these experiments, the light emission from NO was captured in the range of 230-280nm. NO can also be thermally and chemically excited in that range of wavelengths, emitting light through the $\text{A}^2\Sigma=\text{X}^2\Pi$ transition [35]. Simulations performed for NO light emission showed strong signal in this range [36]. Consequently, NO presence can be detected through NO^* chemiluminescence using an appropriate UV filter. A review of molecule spectra indicated that multiple molecules can emit light in the range of 230-270nm, such as PO, CF, SiO, NO, CS, BiO, SO. However, NO is the only molecule that can be present in our experiment, indicating that any signal captured in this range will be a result of NO emission [35]. This captured signal will indicate the presence of NO qualitatively and hence can be used for comparative purposes between different cases examined in this study. It is postulated

that high chemiluminescence signal indicates the presence of large amount of excited NO in an area of high temperature, and a low signal indicates a rather low population of excited NO in a low temperature region. Intermediate signals can be a combination of high NO population in low temperature region or low NO population in high temperature region. In any case, a decrease in the NO signal shall indicate a combination of reduction of NO population and a lower temperature, making this signal (NO chemiluminescence) an additional useful tool to describe reaction distribution.

3. Experimental Facility

The experiments were performed using a swirl burner fueled with methane. Previous experiments have outlined the pollutants emission and reaction distribution under different oxygen concentration through entrainment of different amounts of N₂-CO₂ mixture [16]. The details and performance of this swirl burner have been discussed with focus on pollutants emission and velocity profiles using methane and hydrogen enriched methane fuels [37-38].

Air and nitrogen flow rates were controlled by laminar flow controllers having an accuracy of $\pm 0.8\%$ of reading $\pm 0.2\%$ of full scale leading to an overall accuracy of about 1.5% of the reading. Methane and carbon dioxide flow rates were controlled through gravimetric flow controllers having an accuracy of 1.5% of full scale.

To quantify flame characteristics and visual emissions, an ICCD camera coupled to a narrow band filter was used for the appropriate species to be recorded. For OH*, a UV interference filter centered at 307nm with a FWHM of ± 10 nm was used. This filter had a quantum efficiency of about 17%. For CH*, a visible filter centered at 430nm with a FWHM of ± 10 nm was used with an efficiency of 48%. To account for background noise and CO₂* chemiluminescence, two filters

at 410nm and 450 with a FWHM of $\pm 10\text{nm}$ were used. These two filters had an efficiency of about 55%. The signal from both filters was averaged to obtain the noise at 430nm. The CH* signal was corrected as follows

$$\text{CH}_{\text{corrected}} = \text{CH}_{\text{signal}} - [(\text{Signal}_{410} + \text{Signal}_{450})/2] \quad (1)$$

where, $\text{CH}_{\text{corrected}}$ is the background corrected CH chemiluminescence image, $\text{CH}_{\text{signal}}$ is the raw signal captured at 430nm, Signal_{410} is the efficiency corrected signal captured at 410nm and Signal_{450} is the efficiency corrected signal captured at 450nm. To account for the difference in efficiencies, a standard mercury calibration lamp was used to verify these efficiencies and obtain conversion factors for different wavelengths. These conversions accounted for different filter efficiencies and for the sensor and intensifier quantum efficiencies at different wavelengths. These conversion factors were used to obtain a true CH*/OH* ratio without any of the filter and camera efficiencies affecting this ratio. The conversion factors are as follow:

$$\text{OH}_{\text{corrected}} = \text{OH}_{\text{signal}} * 1.885 \quad (2)$$

$$\text{Signal}_{410} = \text{RawSignal}_{410} / 2.1733 \quad (3)$$

$$\text{Signal}_{450} = \text{RawSignal}_{450} / 2.1733 \quad (4)$$

where, $\text{OH}_{\text{corrected}}$ is the efficiency corrected OH chemiluminescence image, $\text{OH}_{\text{signal}}$ is the raw signal captured at 307nm, Signal_{410} (or Signal_{450}) is the efficiency corrected signal captured at 410nm (or 450nm) and RawSignal_{410} (or RawSignal_{450}) is the raw signal captured at 410nm (or 450nm).

For NO, a UV interference filter centered at 248nm with a FWHM of $\pm 15\text{nm}$ was used. This filter had a quantum efficiency similar to that of the OH* filter (307nm with a FWHM of $\pm 10\text{nm}$); consequently they can be directly compared as the camera had the same detection efficiency for this wavelength range.

The signals were recorded using the five filters discussed (248nm, 307nm, 410nm, 430nm, and 450nm) one after the other, and the images were processed to account for any shift to the camera that might happen during filter change. The gain was kept constant for all the experiments with an exposure time of 100ms. For each experimental condition and filter, 10 shots were averaged together to produce the raw signal that was then processed to account for noise and quantum efficiencies as described earlier.

The experimental rig is shown in Fig. 1, along with the flame at two different conditions of standard air combustion wherein the swirl structure is dominant, and reduced oxygen concentration combustion showing near distributed combustion with less visible emission. Thermocouples were fitted along the reactor walls to confirm the existence of reaction zone at low oxygen concentration as the flame was invisible with almost no combustion noise.

4. Experimental Investigations

The experimental investigations reported herein were aimed at examining the reaction behavior and distribution with different amount of dilution (different oxygen concentration in the mixture) and compare the behavior for NO and CO emission. Oxygen concentration was varied through supplying different amounts of N₂-CO₂ dilution mixture (90%-10% by volume). First, experiments were performed under two equivalence ratio (0.9 and 0.7). Afterwards, the experiment was repeated using preheated diluents (600K) for simulating recirculated gases from within the combustor.

Table 1 summarizes the conditions reported here along with the variables manipulated for each case. For each heat load, the fuel flow rate was kept constant while the air flow rate was changed to change the equivalence ratio. For every equivalence ratio, air and fuel flow rates were

220 kept constant while the amount of $\text{N}_2\text{-CO}_2$ mixture was increased to lower the oxygen concentration in the mixture prior to ignition.

5. Results and Discussion

5.1 *Experiments with Diluents at 300K*

225 Experiments conducted using $\text{N}_2\text{-CO}_2$ mixtures at 300K were at a heat load of 3.25 kW using constant fuel flow rate. Air flow rate was changed to result in different equivalence ratios (0.9 and 0.7). Changing the relative amounts of $\text{N}_2\text{-CO}_2$ in the mixture provided change in oxygen concentration change, down to 13.8%. Figure 2 shows flame images for the case of no dilution (normal 21% oxygen concentration air) and different dilution amounts (down to 13.8% O_2) at an equivalence ratio of 0.9. As the diluents amount was increased, the flame became more distributed and of uniform shape, covering a larger portion of the combustor with a decrease in visible flame signature. This reduction in visible flame signature was also accompanied by reduction in combustion noise. As the oxygen concentration was decreased NO emission decreased while CO emissions remained constant until instabilities were observed (at oxygen concentration lower than about 13.8%) [16].

235 These images provide a global description of how the reaction zone changes with different diluents and oxygen concentration reduction. To further understand the reaction behavior and distribution, chemiluminescence emission signal was captured at different wavelengths (specific to OH^* and CH^*). The obtained images are shown in Fig. 3 for filter wavelengths of 307nm (OH^*) and 430nm (CH^*). The images obtained at 410 and 450 nm, that correspond to background noise and CO_2^* chemiluminescence, are also given and are used here for background correction.

The signals captured at 307nm (OH*), 410nm and 450nm were corrected following equations (2-4) to account for different camera and filter efficiencies as compared to the signal captured at 430nm (CH*). The corrected signals are shown in Fig. 4 along with the raw CH* signal scaled to the same scale.

By accounting for the different filter transmission efficiencies and camera quantum efficiency, one can obtain a corrected CH* plot (corrected for background and CO₂* chemiluminescence) following equation (1). The corrected CH* signal is then divided by corrected OH* signal to provide a measure of the equivalence ratio and reaction distribution within the reaction zone. A Matlab code was employed to handle the images subtraction and division with a subroutine to detect the image boundaries and correct for any shift that might have occurred during filter change and installation. Figure 5 shows the obtained CH*/OH* ratio for the different dilution cases (oxygen concentrations of 21% to 13.8%) at an equivalence ratio of 0.9 with focus on the flame region.

Increase in the diluents amount (decrease in oxygen concentration) resulted in lower CH*/OH* signal and that the signal emission distribution covered a larger portion of the combustor. For the case of no dilution, the CH*/OH* ratio was between 0.4 and 0.6 with some local spots of higher values. As the oxygen concentration was decreased, this ratio decreased to an average of 0.35 for oxygen concentration of 15.58%. For oxygen concentration of 13.8%, the ratio was widespread (as seen from Fig. 2 of the visible flame emission signatures,) with CH*/OH* value of 0.2 or less.

Following the work of Muruganandam et al.[28], one can convert these ratios to equivalence ratios based on similarity in Reynolds number (~10000) between their work and this study in the

swirl combustor experiments. For the conversion, the data reported by Muruganandamet al. [28] was curve fitted and an equation relating the CH*/OH* to equivalence ratio was given as:

$$\text{Phi} = -1.1184 (\text{CH}^*/\text{OH}^*)^2 + 1.5361 (\text{CH}^*/\text{OH}^*) + 0.44 \quad (5)$$

where, Phi represents the equivalence ratio. This curve fit had a regression coefficient of 0.975 with a maximum difference of 5% between measured values [28] and the calculated values from equation (5). Figure 6 shows the respective equivalence ratios obtained by applying equation (5) to the data shown in Fig. 5.

For the case of no dilution, the equivalence ratio was 0.95 at its highest (at the swirl lobes) and decreased as one moved further downstream. This is expected from swirl flames wherein the flame is anchored at the shear layer in the central recirculation zone. As one moves further away from this shear layer the reaction signature diminishes from the completed combustion due to the availability of excess air. It is noteworthy that the global equivalence ratio in this case is 0.9; however, the local ratio varies as air and fuel are injected in non-premixed method. Fuel is injected directly after the swirler and the reaction is expected to occur at an equivalence ratio close to stoichiometry (similar to a diffusion flame) regardless of the global equivalence ratio. The deviation between the obtained value (0.95) and stoichiometry can be attributed to the mixing process between air and fuel jet.

Increase in the amount of diluents decreased the maximum value of the equivalence ratio (0.85~0.9 at oxygen concentrations of 17.89% and 16.65%). Further increase in diluents (decrease in oxygen concentration) resulted in a more distributed and uniform equivalence ratio across the combustor with the reaction zone occupying a larger area. Also, at these lower oxygen concentration and increased dilution, the characteristic zones associated with swirl burners disappear and a more uniform and dispersed reaction zone occurs. At oxygen concentration of

15.58%, the local equivalence ratio varied between 0.75 and 0.8, while at the lowest oxygen concentration of 13.8% the local equivalence ratio average was about 0.68.

290 To better characterize the reaction distribution, statistical analysis was performed on the obtained equivalence ratio. Figure 7 shows the variation of the mean and standard deviation with different dilution amounts and oxygen concentration. There is minimal variation in the mean value. This can be attributed to the fact that in high oxygen concentration (21%), the high value of local equivalence ratio is offset by the lower values outside the flame zone. On the other hand
295 at low oxygen concentration, the values are closer to each other, with almost no zero values (due to the distributed flame nature) to result in a similar mean value. This is supported by the standard deviation values. At high oxygen concentration the standard deviation is high, indicating that values deviate from the mean with a greater extent, while it is low for the low oxygen concentration case, indicating a more uniform value, more close to the mean. This low
300 standard deviation outlines distributed reaction combustion demonstrated at low oxygen concentration.

It is important to note that, in all the cases, the oxygen to fuel ratio did not change since only the oxygen concentration (through addition of diluents) was reduced. Consequently, the obtained equivalence ratios discussed herein are not the actual equivalence ratios, but rather a
305 representation of the reaction behavior. In other words, by having oxygen concentration of 13.8% (through dilution) resulted in a flame behavior that are similar to that of a flame at an equivalence ratio of 0.68 as seen through OH* and CH* chemiluminescence. More importantly, with increased dilution, the variation of equivalence ratio was minimized with the reaction covering a larger volume with a better distribution and elimination of concentration reaction
310 zone such as that observed in the central recirculation zone of swirl combustors. These

characteristics are signatures of distributed reaction combustion that is desirable for ultra-low emissions and enhanced thermal field uniformity.

The experiments were performed at an equivalence ratio of 0.7 with focus on fuel-lean operation. Similar to the results discussed at equivalence ratio of 0.9, the flame occupied larger portion of the combustor as the oxygen concentration was decreased through dilution. Figure 8 shows the obtained equivalence ratio plots using CH^* and OH^* chemiluminescence. Although the global equivalence ratio was 0.7, the air and fuel were injected in a non-premixed mode leading to reaction occurring at a different equivalence ratio other than the global one, leading to the higher measurement with no dilution case, where the measured equivalence ratio was close to 0.9. As the amount of diluents was increased, the maximum value of the equivalence ratio decreased from 0.9 (for oxygen concentrations of 21%) down to 0.7 (at oxygen concentration of 16.5%). Moreover, the equivalence ratio variation decreased throughout the flame area leading to a distributed reaction for at low oxygen concentration. The mean of the signal decreased from 0.6819 to 0.6065 with decrease in oxygen concentration from 21% to 16.5% and the standard deviation decreased from 0.1241 to 0.0648 for the same cases, demonstrating better distributed reaction at the lower oxygen concentration.

5.2 *Experiments with Diluents at Elevated Temperatures*

To examine the impact of diluents temperature on flame behavior at elevated temperatures, the experiments were performed with diluents temperature at 600K. The heat load of the combustor was kept at 3.25 kW and air was supplied to the combustor to result in an equivalence ratio of 0.9. The obtained OH^* and CH^* results were processed as outlined earlier to obtain the local equivalence ratios. Increase in the diluents temperature resulted in higher NO emission as

compared to that obtained at diluents temperature of 300K [16]. However, increase in the
335 diluents temperature allowed stable combustor operation at lower oxygen concentration (down to
10.73% as compared to 13.8%) [16]. Figure 9 shows the equivalence ratio plots for diluents
temperature of 300K and 600K at an equivalence ratio of 0.9 and oxygen concentration of
16.65%.

As the diluent temperature was increased, the reaction area was enlarged, with higher signal
340 values across the combustor, as compared to the case of diluents injected at 300K. This increase
in signal corresponds with the increase in pollutants emissions reported previously [16].

Figure 10 shows the change in reaction behavior with increased dilution (decrease in oxygen
concentration) at a diluent temperature of 600K. As the amounts of diluents increases, the
reaction occupies a larger area at lower local equivalence ratio. At oxygen concentration of
345 16.65%, the maximum equivalence ratio was about 0.95 with an average of 0.89. Further
reduction in oxygen concentration resulted in lower maximum and mean values (0.8 and 0.72 at
O₂ of 13.8%, 0.75 and 0.65 at O₂ of 11.78%). The standard deviation of the signal was also
decreased from 0.126 (at 16.65% O₂) to 0.0686 (at 11.78% O₂) resulting in a better reaction
distribution from improved distributed combustion conditions.

5.3 *NO* Chemiluminescence*

The chemiluminescence of NO was also obtained to determine its behavior with change in
dilution and oxygen concentration. Figure 11 shows the NO signal, obtained at 248nm, as
compared to the OH signal (at 307nm) for equivalence ratio of 0.9 with no dilution. The
355 difference between both signal intensity is significant with NO signal being almost one order of
magnitude smaller than OH signal (for the same exposure time and gain). For both signals, the

filters and camera had the same efficiency allowing direct comparison between the two signals. Note that for the NO signal ($248\text{nm} \pm 15\text{nm}$), the filter bandwidth is well outside the OH band around 283nm (from the (1,0) vibrational band), eliminating any possibility of OH chemiluminescence present in the NO signal.

Figure 12 shows the change in both OH* and NO chemiluminescence signal with change in dilution. As the dilution increases (and oxygen concentration decreases), both OH* signal and NO signal decreased in intensity with a rather distributed nature as compared to their concentrated nature with no dilution. The signals are scaled differently for better signal detection at high dilution and low oxygen concentration. Comparing both signals, one can see that the NO signal coincides with maximum OH* signal. Also, both signals behave similarly in terms of occupying larger volume at decreased intensity at increased entrainment and reduced oxygen concentration. This behavior translated to a reduction in NO emission for the same conditions, from 13.3 PPM of NO (at 21% O₂) to 2.23 PPM of NO (at 13.8% O₂) as reported previously [16] and shown in Fig 13.

Experiments at lower equivalence ratio demonstrated the same trend wherein the NO signal decreased with increase in dilution (reduction in oxygen), following the trend of OH* chemiluminescence. This is evident from comparison of the case with no dilution (21% O₂), wherein NO signal is recorded near the central recirculation zone, and with increased dilution (18.5% O₂), wherein NO signal was uniformly distributed throughout the reaction zone area. Further reduction in oxygen concentration did not affect the NO signal much. This can be attributed to the existing conditions for these cases. At these dilution amounts and oxygen concentration, thermal NO_x is mitigated and the resulting NO emission is attributed to other NO_x formation routes. This behavior was reflected through NO emissions, where NO was reduced

380 from 6.6 PPM (at 21% O₂) to 2 PPM (at 18.5% O₂) but only down to 1 PPM (at 16.5% O₂) as shown in Fig. 13. Figure 14 shows the recorded NO chemiluminescence signal emission for the discussed cases.

Experiments performed at higher diluents temperature demonstrated the same behavior wherein NO signal followed the trend of OH* chemiluminescence in terms of maximum
385 concentration and distribution with increased dilution. The NO signal recorded agrees with the previously recorded emissions. NO emissions decreased from 13.3 PPM NO at no dilution down to 1.6 PPM for oxygen concentration of 11.78%, see Fig 13. Figure 15 shows the recorded NO chemiluminescence signal for these cases, where the concentrated NO signal at the recirculation zone (for no dilution) disappears with increased dilution to result in distributed low NO signal at
390 low oxygen concentration.

6. Conclusions

Experiments performed at different reduced oxygen concentration in the fresh mixture, at a global equivalence ratio of 0.9, provided significant change to the reaction behavior. For the case
395 of normal air (no dilution), the reaction zone was concentrated near the central recirculation zone of the swirler. The swirl characteristics disappeared with increase in the amounts of dilution, to result in a more distributed reaction zone occupying larger volume of the combustor. CH*/OH* was used to obtain a representation of local equivalence ratio for the different cases. As the oxygen concentration was decreased, the maximum equivalence ratio decreased with the mean
400 approaching the maximum value along with a lower standard deviation of the signal. Closer mean to maximum signal, coupled with lower standard deviation for the equivalence ratio indicates improved distributed reaction conditions. These conditions were fostered at oxygen

concentration of 15% and lower. This oxygen concentration is approximately where the swirl characteristics disappear resulting in improved distributed reactions. Similar behavior was demonstrated at lower equivalence ratio of 0.7. With diluents preheated to 600K, the reaction transformed to distributed combustion regime upon lowering of the oxygen concentration. Higher temperature of the diluents allowed stable combustion at lower oxygen concentration.

Chemiluminescence signal outlined the presence of NO in the reaction zone with reduced signal intensity at increased dilution. The NO signal followed the maximum OH* signal in location and behavior. Reducing oxygen concentration led to lower NO distribution in the combustor

The obtained data on local equivalence ratio (as well as uniform CH*/OH* signal) and NO emission (quantified through NO light emission and emission measurement suggests that to foster distributed combustion conditions (CDC), oxygen concentration of 15% is favored in the fresh mixture. Such oxygen concentration will dictate the required internal entrainment ratio at a given combustion operation.

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Figure Captions

Figure 1. Experimental test rig with flame using standard air (left) and reduced oxygen concentrations (right)

Figure 2. Flame images for different oxygen concentration (with change in diluents amount) for an equivalence ratio of 0.9

Figure 3. Acquired signal for no dilution case at an equivalence ratio of 0.9 for the different filters used

Figure 4. Acquired signal for no dilution case at an equivalence ratio of 0.9 corrected for different filter and camera efficiencies

Figure 5. CH^*/OH^* chemiluminescence signal at an equivalence ratio of 0.9 for different dilution cases (oxygen concentration variation from 21% to 13.8%)

Figure 6. Local equivalence ratio obtained from equation 5 for different dilution cases (oxygen concentration variation from 21% to 13.8%) at a global equivalence ratio of 0.9

Figure 7. Mean and standard deviation of the equivalence ratio for different dilution cases (oxygen concentrations variation from 21% to 13.8%) at a global equivalence ratio of 0.9

Figure 8. Local equivalence ratio as obtained from equation 5 for different dilution cases (oxygen concentrations variation from 21% to 16.51%) at a global equivalence ratio of 0.7

Figure 9. Local equivalence ratio as obtained from equation 5 for 300K (left) and 600K (right) dilution temperature at a global equivalence ratio of 0.9

Figure 10. Local equivalence ratio as obtained from equation 5 at a global equivalence ratio of 0.9 and 600K diluents temperature

Figure 11. OH^* and NO signal at an equivalence ratio of 0.9 with no dilution

Figure 12. NO (top row) and OH^* (bottom row) chemiluminescence signal with increased dilution (decreased oxygen concentration) at an equivalence ratio of 0.9

Figure 13. NO emission for equivalence ratio of 0.9 at 300 and 600K, and equivalence ratio of 0.7 at 300K [16]

Figure 14. NO chemiluminescence signal with increased dilution (decreased oxygen concentration) at an equivalence ratio of 0.7

Figure 15. NO chemiluminescence signal with increased dilution (decreased oxygen concentration) at an equivalence ratio of 0.9 for diluents temperature of 600K

Table Captions

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Table 1. Experimental parameters

Heat Load	Heat Release Intensity [MW/m ³ -atm]	Mixture Temperature	Equivalence Ratio	Oxygen Concentration [%]
3.25 kW	2.4	300K	0.9	21-13.8
3.25 kW	2.4	300K	0.7	21-16.5
3.25 kW	2.4	600K	0.9	21-10.7
3.25 kW	2.4	600K	0.7	21-14.9