KMUTNB Int J Appl Sci Technol, Vol. 9, No. 1, pp. 37–43, 2016

Internal Entrainment Effects on Distributed Combustion

Ashwani K. Gupta * ***and Ahmed E. Khalil***
Department of Mechanical Engineering, Faculty of Engineering, University of Maryland, College Park, Maryland, USA

* Corresponding author. E-mail: akgupta@umd.edu

DOI: 10.14416/j.ijast.2016.01.002
Received: 9 December 2015; Accepted: 11 January 2016;

Abstract

Colorless Distributed Combustion (CDC) has been shown to provide ultra-low emissions and enhanced combustion performance of high intensity gas turbine combustors in terms of efficiency and stability. To achieve distributed combustion, the flowfield needs to be carefully tailored for adequate mixing between reactants and hot reactive species from within the combustor to result in high temperature low oxygen concentration environment prior to ignition. Such distributed reactions result in uniform thermal field and also eliminates any hot spots for mitigating NO_x emission. Though Distributed Combustion have been extensively studied using a variety of geometries, injection velocities, heat release intensities, and fuels, the role of hot reactive internally recirculated gases requires further examination. In this paper, the impact of internal entrainment of reactive gases on flame structure and behavior is investigated with focus on fostering distributed combustion and providing guidelines for designing high intensity combustors operating in distributed combustion mode. A mixture of nitrogen and carbon dioxide, used to simulate the recirculated gases, is introduced to the air stream prior to mixing with the fuel and subsequent combustion. Increase in the amounts of nitrogen and carbon dioxide (simulating increased entrainment), led to volume distributed reaction over a larger volume in the combustor with enhanced and uniform distribution of the OH* chemiluminescence intensity. At the same time, the bluish flame stabilized by the swirler is replaced with a more uniform almost invisible bluish flame. The increased recirculation also reflected on the pollutants emission, where NO emissions were significantly decreased for the same amount of fuel burned. Lowering oxygen concentration from 21% to 15% (due to increased entrainment) resulted in 80–90% reduction in NO with no impact on CO emission with sub PPM NO emission achieved at an equivalence ratio of 0.7. The same trend was seen at higher diluents injection temperature as well, with significant pollutants emission reduction down to an oxygen concentration of 10%.

Keywords: Colorless distributed combustion, Ultra low NO_x, High intensity gas turbine combustion, Reactive gas entrainment, High temperature air combustion, Green combustion turbine

1 Introduction

The increased role of natural gas and shale gas in electricity and power generation have motivated combustion researchers to develop advanced energy conversion systems that can furnish the current and future energy needs with minimal impact on the environment using these local energy sources. These combustion systems need to comply with the stringent emission regulations and form a pivotal part of the quest for environmentally friendly energy systems. The combustion systems shall also achieve near zero emission of pollutants (such as, NO_x, CO, unburned hydrocarbons and soot) from the enhanced thermal

Please cite this article as: A. K. Gupta and A. E. Khalil, "Internal entrainment effects on distributed combustion," *KMUTNB Int J Appl Sci Technol*, vol. 9, no. 1, pp. 37–43, Jan.–Mar. 2016.

field uniformity to prevent local burnout and downtime of the equipment. In this aspect, colorless distributed combustion (CDC), which shares some of the principles of high temperature air combustion (HiTAC) [1], has been shown to provide the benefits of reducing the emissions of NO and CO, and improving the pattern factor (enhance thermal field uniformity in the entire combustor). Reduced noise and stable combustion have also been shown under CDC conditions for high intensity gas turbine combustion condition. 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 from the flames as compared to conventional flames.

Colorless distributed combustion (CDC) is focused on high intensity gas turbine combustors for both stationary and aviation applications. Previous investigations on CDC have shown significant improvement in pattern factor, low noise emission levels and ultra-low emissions of NO and CO [2]–[5]. Critical requirement to achieve distributed reactions is controlled and rapid mixing between fresh reactants and hot reactive species from within the combustor to provide spontaneous ignition of the resulting mixture. The distributed reactants results in distributed reaction rate over the entire volume of the combustor rather than the concentrated thin flame front characterized by high reactions rates with local hot spots. The distributed combustion regime not only avoids the formation of thin reaction zone, it also avoids the hot-spot regions in the flame to mitigate thermal NO_x emissions produced from the Zeldovich thermal mechanism [1], [6].

The importance of good preparation of the air, fuel, and hot reactive species mixture for ignition cannot be overstated. The role of swirling air injection into the combustion chamber for seeking distributed combustion reactions was explored. The tangential air jet entrains large amounts of product gases from within the combustion chamber. The amounts of entrainment are controlled to increase the temperature of the reactant mixture to a level higher than auto-ignition temperature of the fuel. The uniformly mixed fuel/air/hot active gases then spontaneously ignite to result in a distributed reaction regime, instead of a thin concentrated reaction flame front [3]–[5]. The mixing of hot reactive gases with the fresh mixture helps to increase temperature of the mixture to cause spontaneous ignition in the entire combustion zone as compared to only small region of the fresh mixture as exhibited in conventional flames for flame stabilization. Ultra-low NO emission along with low CO emission have been demonstrated for swirling CDC combustor [4] under premixed combustion mode, with emission below 5 PPM of NO at a heat release intensity of 27 MW/m^3-atm at a rather high equivalence ratio of 0.6 with air preheats temperature of 600K to simulate gas turbine combustor inlet temperatures. Emissions below 2 PPM have been also demonstrated for normal intake air temperature [3]. Swirling CDC have been investigated using different fuel introduction scenarios [5], fuels [7], and injection velocities [8]. In all cases, ultra-low emissions were demonstrated.

For all these investigations, increased entrainment of recirculated hot reactive gases decreased emissions and enhanced thermal field uniformity in the combustion chamber. However, further investigations are required to precisely determine the amounts of hot reactive species needed to foster distributed reaction conditions. Increased recirculation of reactive species lowers the mixture oxygen concentration and increases the mixture temperature prior to ignition, and consequently controlling the fate of the reaction distribution. Previous experiments have investigated the conditions (oxygen concentration and temperature) to achieve distributed reactions in furnaces [9], which are characterized by lower thermal intensity and near stoichiometric (richer fuel) combustion as compared to gas turbines. For methane, it was found that oxygen concentration of about 8% or lower results in a colorless flame. In another investigation, the flame temperatures have been measured, showing that the reaction is much more distributed at 4% oxygen concentration as compared to 21% oxygen in air. This was demonstrated with and without air preheats prior to combustion [10], however, experiments were only performed at those two oxygen concentrations.

Other researchers investigated the impact of recirculating exhaust gas (Exhaust Gas Recirculation, EGR) on the performance of gas turbine. In one study, 40% reduction in NO_x has been demonstrated with 35% EGR, leading to oxygen concentration of 17% [11]. In another investigation, it was determined that operation at full speed full load with EGR is an acceptable condition up to 30% EGR, in absence of acoustic instabilities and with good efficiency of combustion [12].

Obtaining low oxygen concentrations in the mixture prior to ignition can be challenging for gas turbine applications. Gas turbine traditionally run lean, resulting in an oxygen concentration of 8% or so in the products, indicating that large amounts of recirculation will be needed to achieve oxygen concentrations below about 15%. Such large recirculation requirement poses a problem for combustor flowfield design.

In this paper, the impact of the amount of gas recirculation is investigated with focus on determining the minimum requirements for distributed reactions to occur (hot gas entrainment/oxygen concentration). For that, a swirl burner is used and emissions (NO and CO) and flame behavior are measured for different amounts of entrainment. A mixture of nitrogen and carbon dioxide (90%–10% by volume) is used to simulate exhaust gases. Furthermore OH* chemiluminescence intensity was captured to outline the reaction zone behavior under different operational conditions.

2 Experimental Facility

The experiments were performed using a swirl burner fuelled with methane. Details of this swirl burner can be found in the literature [13]. The performance of this swirl burner has been studied in terms of emissions and velocity profiles using methane and hydrogen enriched methane [13]–[14]. 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 fuel was injected right after the swirler in a non-premixed configuration.

Air and nitrogen flow rates were controlled by laminar flow controllers with an accuracy of ±0.8% of reading ±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 a gravimetric flow controller with an accuracy of 1.5% of full scale.

Detailed investigations on the overall emissions from the combustor as well as visible emissions have been performed for the various experimental conditions. 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 a minimum of three times for each configuration and the uncertainty was estimated to be about ±0.5 PPM for NO and ±10% for CO emission.

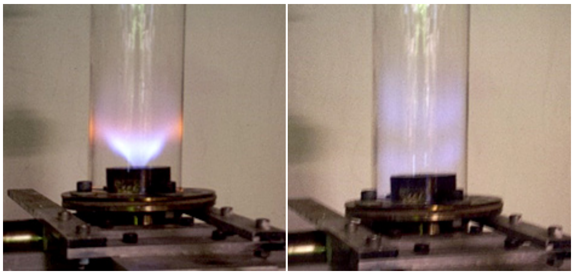
(a) (b)

Figure 1: Experimental test rig with flame using normal air (a) and reduced oxygen concentrations (b).

For imaging the OH* chemiluminescent intensity distribution, an ICCD camera coupled to a narrow band filter, centered at wavelength 307 nm wavelength, was used. The resulting OH* intensity distributions were then normalized to have the same scale. A photograph of the experimental test rig is shown in Figure 1, along with the flame under normal air combustion, where the swirl structure is dominant, and also under conditions of reduced oxygen concentration combustion, showing near distributed combustion with less visible emissions. Thermocouples were fitted along the reactor walls to confirm the existence of reaction zone at low oxygen concentration as the flame turns to be invisible with almost no combustion noise.

3 Experimental

The experimental investigations reported here were aimed at examining the NO and CO emission as well as OH* chemiluminescence intensity as affected by oxygen concentration prior to ignition. Oxygen concentration was varied through supplying different amount of N_2-CO_2 mixture (90%–10% by volume). The experimental data were obtained at different equivalence ratios and heat loads to determine the emissions and flame trends under different conditions.

The temperature of the injected diluents (N_2-CO_2 mixture) was also varied to outline the role of diluents temperature and allow further reduction in the oxygen concentration simulating increased entrainment.

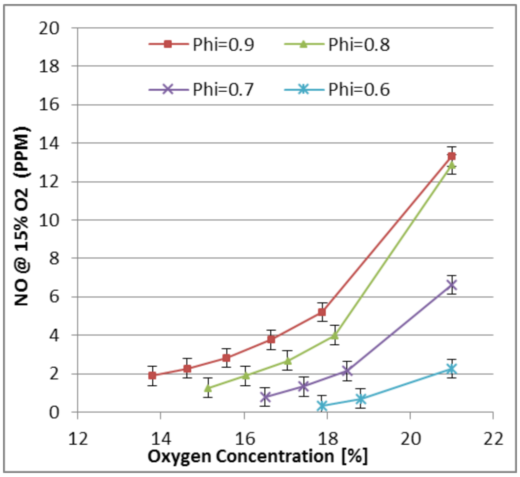

Figure 2: NO emission with change in oxygen concentration in the fresh mixture at different equivalence ratios.

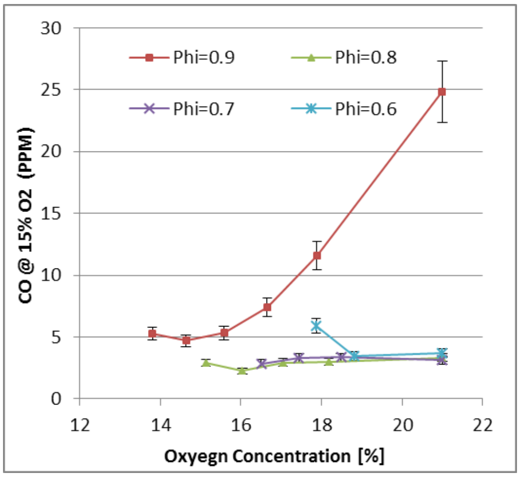

Figure 3: CO emission with change in oxygen concentration in the fresh mixture at different equivalence ratios.

4 Results and Discussion

The experiments performed at a heat load of 3.25 kW involved constant fuel rate and the air flow rate was changed to result in different equivalence ratios. Changing the N_2-CO_2 mixture amounts changed the oxygen concentration in the fresh mixture. Figure 2 shows the NO emission for the different cases presented here.

NO emission decreased significantly with reduction of oxygen concentration in the fresh mixture. NO decreased by some 60% by reducing the oxygen concentration from 21% to about 18%. NO emission lower than 4 PPM was demonstrated regardless of the equivalence ratio as long as the oxygen concentration was lower than 17%. 2 PPM of NO has been shown even at an equivalence ratio of 0.9, which is rather high for stationary gas turbine applications.

Figure 3 shows the CO emissions for the same conditions as shown in Figure 2. Decrease in oxygen concentration enhanced the combustion and led to lower CO emission, especially at the higher equivalence ratios. However, CO emission increased as the oxygen concentration was further reduced. This increase in CO emission was associated with lower temperatures and onset of combustion instability and flame blowout.

Figure 4 shows the recorded OH* chemiluminescence intensity distribution for the different cases presented here. The reduced oxygen concentration through addition of N_2-CO_2 mixture resulted in less concentrated reaction zone and exhibited lower overall intensity. The structure associated with the swirl burner (as seen for the case of no N_2-CO_2 addition) gradually disappeared with oxygen reduction until disappearance at an oxygen concentration of about 14.6% and lower for an equivalence ratio of 0.9. The data was also captured for a lower equivalence ratio of 0.7, where the same trend is exhibited. However, in this case the swirl structure disappeared at higher oxygen concentration (16.5%) compared to the fuel-richer case (14.6%).

The more distributed nature of the OH* signal with decrease in oxygen concentration in the fresh mixture corresponds well with the recorded data on NO emissions shown in Figure 2. The more distributed the reaction, the lower the NO emission. The OH* chemiluminescence data suggests that the reaction is rather distributed for lower oxygen concentrations (lower than 16% for phi=0.9 and lower than 17% for phi=0.7), indicating that this value (obtained for each equivalence ratio) should be targeted through reactive gases entrainment. This value is also supported through NO emission, where minimal NO emission was obtained by lowering the oxygen concentration (lower than 16% for phi=0.9 and lower than 17% for phi=0.7).

The enhanced distribution with lower oxygen concentration reflected on the visible emissions as well. As the oxygen concentration was reduced, the flame changed from blue to faint bluish color to almost

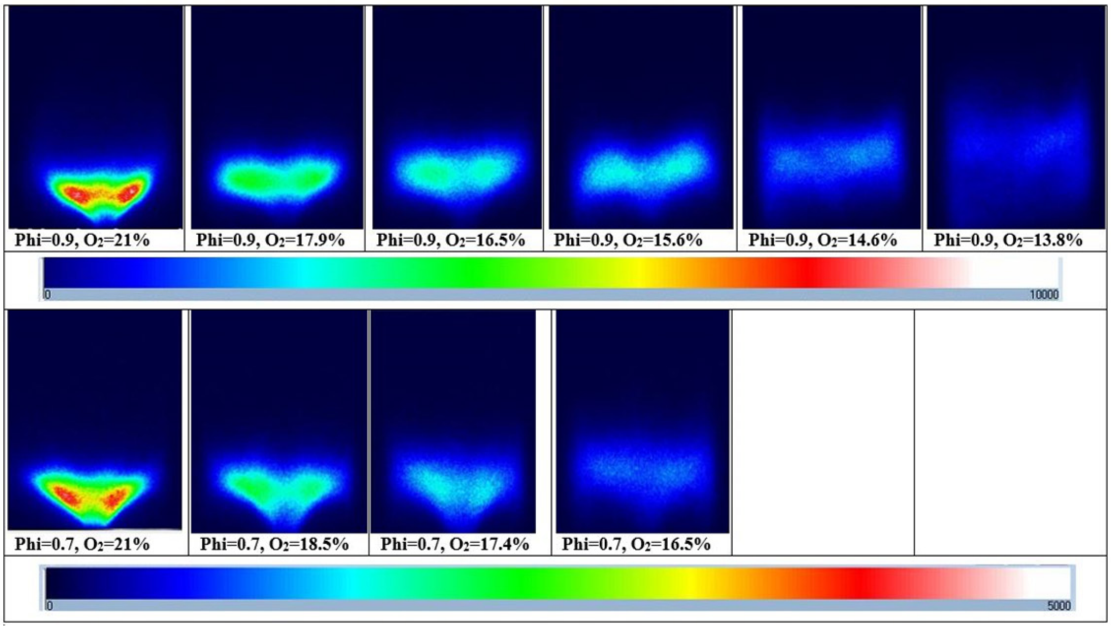

Figure 4: OH* Chemiluminescence intensity distribution for different equivalence ratio and oxygen concentration.

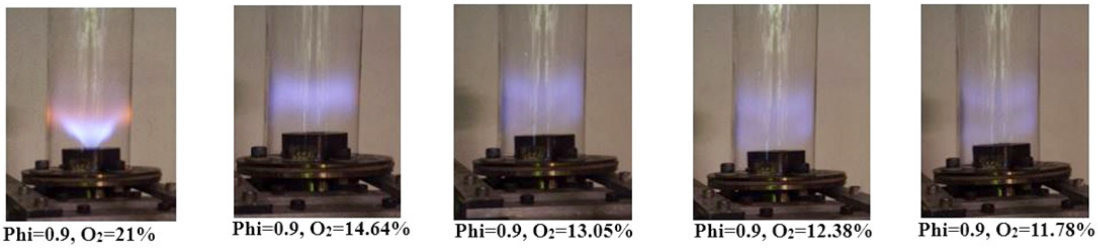

Figure 5: Change in flame visible emissions with increasing N_2-CO_2 amounts (reducing O_2 concentration).

invisible flame, see Figure 5, indicating distributed combustion conditions. Also the characteristic swirling flame structure diminished with increased entrainment to result in a more distributed flame.

The experiments were also performed with focus on the role of dilution gases temperature on emissions. All the previous experiments were aimed at identifying the impact of oxygen concentration reduction (which can be achieved in actual combustion systems through reactive gas entrainment). However, such entrainment will increase the fresh mixture temperature. In the case of internal entrainment, the gases will have temperature of 1500K or higher. The N_2-CO_2 mixture was preheated to different temperatures with view to understand the impact of diluents temperature on emissions and flame stability.

Figure 6 shows the NO emission for different preheat temperature at equivalence ratios of 0.9 and 0.7. Increase in the mixture temperature slightly increased the NO emission at a given oxygen concentration. For instance, at phi=0.9 and 15.6% O_2, NO emission increased from 2.8 PPM at T=300K, to 3.7PPM for T=450K, and 3.9 PPM at T=600K. NO emission lower than 2 PPM was demonstrated for oxygen concentration lower than 12%. On the other hand, increasing temperature stabilized the flame at lower oxygen concentration. At T=300K, the burner was stable down to oxygen concentration of 13.8%. Increase in temperature increased this limit to lower oxygen concentration of 12.4% (at 450K), 10.8% (600K), and 10.2% (750K).

Similar performance was obtained at leaner equivalence ratio of 0.7, though the increase of

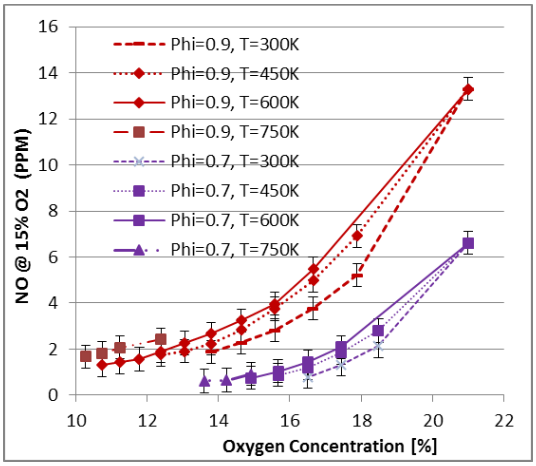

Figure 6: NO Emission variation with change in oxygen concentration for different N_2-CO_2 temperature.

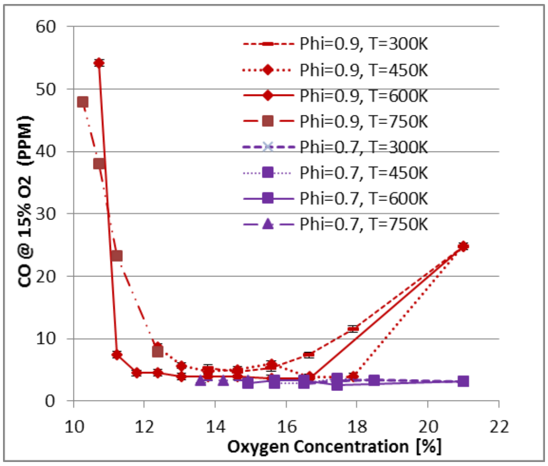

Figure 7: CO Emission variation with change in oxygen concentration for different N_2-CO_2 temperature.

emissions with increase in temperature was much lower (0.6 PPM increase between 300K and 600K at O_2 concentration of 16.5%). Similarly the stable combustion operation was extended to 13.6% at higher temperature (750K) as compared to 16.5% O_2 for T=300K.

The impact of increasing temperature had a significant impact on CO emission. Higher diluents temperature led to lower CO emission at equivalence ratio of 0.9. This is attributed to the higher overall combustion temperature and more energy available for complete CO to CO_2 conversion. For the lower equivalence ratio of 0.7, CO emission did not change much. The change in CO (1 PPM between maximum and minimum point at a given oxygen concentration) at this equivalence ratio is within the range of experimental error and accuracy of the gas analyzer. Figure 7 shows the recorded CO emissions.

Reduction of the oxygen concentration down to about 16% requires knowledge on the combustor operational equivalence ratio (that dictates the amount of excess oxygen concentration in the hot gases inside the combustor). If the combustor is operated at an equivalence ratio of 0.6, achieving an oxygen concentration of 16% will dictate an entrainment ratio of 1 (i.e., amount of hot entrained gases equal to the fresh air intake) [15]. If the combustor operates at a richer condition, less entrainment will be required and vice versa.

5 Conclusions

Experiments were performed with different amount of nitrogen-carbon dioxide mixture added to the fresh air prior to combustion. This added gas mixture aided in simulating the impact of internal entrainment of hot product gases from within the combustor to result in low oxygen concentration environment prior to ignition.

Results obtained with different reduced amounts of oxygen concentration in the fresh mixture led to significant decrease in NO emission with minimal impact on CO emission. NO emission was reduced by more than 60% and emission lower than 4 PPM were demonstrated regardless of the operational equivalence ratio (at oxygen concentration of 17%). Lower NO emissions were also demonstrated with further reduction of O_2 concentration. OH* chemiluminescence showed a significant reduction in signal intensity with oxygen concentration of 17% or lower where the swirl structure disappears and a more distributed reaction dominates. This behavior agrees well with the reduction of NO emission at these concentration for the various equivalence ratio examined.

Oxygen reduction by about 3% (down to 18%) resulted in about 60% NO reduction to outline the significant impact of oxygen concentration in the mixture on the resulting emissions. Further investigations using preheated nitrogen and carbon dioxide mixtures to simulate internal entrainment of hot reactive gases from within the combustor demonstrated a similar trend where NO emissions were significantly decreased with a rather distributed flame at an oxygen concentration of 16% and lower with minimal impact on CO emissions. Future experiments will focus on higher diluents preheat to reach temperatures equivalent to that of internally recirculated gases.

Acknowledgments

This research was supported by ONR and is gratefully acknowledged.

References

[1] H. Tsuji, A. K. Gupta, T. Hasegawa, M. Katsuki, K. Kishimoto, and M. Morita, *High Temperature Air Combustion: from Energy Conservation to Pollution Reduction*, Boca Raton, Florida: CRC Press, 2003.

[2] V. K. Arghode and A. K. Gupta, "Effect of flowfield for Colorless Distributed Combustion (CDC) for gas turbine combustion," *Applied Energy*, vol. 78, pp. 1631–1640, 2010.

[3] A. E. E. Khalil and A. K. Gupta, "Swirling distributed combustion for clean energy conversion in gas turbine applications," *Applied Energy*, vol. 88, pp. 3685–3693, 2011.

[4] A. E. E. Khalil and A. K. Gupta, "Distributed swirl combustion for gas turbine application," *Applied Energy*, vol. 88, pp. 4898–4907, 2011.

[5] A. E. E. Khalil, A. K. Gupta, K. M. Bryden, and S. C. Lee, "Mixture preparation effects on distributed combustion for gas turbine applications," *Journal of Energy Resources Technology*, vol. 134, no. 3, 2012.

[6] S. M. Correa, "A review of NO_x formation under gas-turbine combustion conditions," *Combustion Science and Technology*, vol. 87, pp. 329-362, 1992.

[7] A. E. E. Khalil and A. K. Gupta, "Fuel flexible distributed combustion with swirl for gas turbine engines," *Applied Energy*, vol. 109, pp. 267–274, 2013.

[8] A. E. E. Khalil and A. K. Gupta, "Velocity and turbulence effect on distributed combustion for clean gas turbine engines," *Applied Energy*, vol. 125, pp. 1–9, 2014.

[9] A. K. Gupta, "Thermal characteristics of gaseous fuel flames using high temperature air," *Journal of Engineering for Gas Turbines and Power*, vol. 126, no. 1, pp. 9–19, 2004.

[10] K. Kitagawa, N. Konishi, N. Arai, and A. K. Gupta, "Temporally resolved 2-D spectroscopic study on the effect of highly preheated and low oxygen concentration air on combustion," *Journal of Engineering for Gas Turbines and Power*, vol. 125, pp. 326–331, 2003.

[11] A. M. ElKady, A. Evulet, A. Brand, T. P. Ursin, and A. Lynghjem, "Exhaust gas recirculation in DLN F-Class gas turbines for Post-Combustion CO2 capture," presented at ASME Turbo Expo 2008: Power for Land, Sea and Air, GT2008, Berlin, Germany, Paper GT2008-51152, June 9–13, 2008.

[12] A. Evulet, A. M. ElKady, A. Brand, and D. Chinn, "On the performance and operability of GE's dry low NO_x combustors utilizing exhaust gas recirculation for post-combustion carbon capture," *Energy Procedia*, vol. 1, pp. 3809–3816, 2009.

[13] H. S. Kim, V. K. Arghode, M. B. Linck, and A. K. Gupta, "Hydrogen addition effects in a confined swirl-stabilized methane-air flame," *International Journal of Hydrogen Energy*, vol. 34, no. 2, pp.1054–1062, 2009.

[14] H. S. Kim, V. K. Arghode, and A. K. Gupta, "Flame characteristics of hydrogen-enriched methane-Air premixed swirling flames," *International Journal of Hydrogen Energy*, vol. 34, no. 2, pp. 1063–1073, 2009.

[15] A. E. E. Khalil and A. K. Gupta, "Towards distributed combustion for ultra-low emission using swirling and non-swirling flowfields," *Applied Energy*, vol. 121, pp. 132–139, 2014.