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Impact of internal entrainment on high intensity distributed combustion

Ahmed E.E. Khalil, Ashwani K. Gupta *

Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA

HIGHLIGHTS

- Examined the role of entrainment on Distributed Combustion under different conditions.
- N_2 and CO_2 are used to simulate entrained combustion gases from within the combustor.
- Low O_2 concentration in the mixture prior to ignition fostered distributed reaction.
- Reaction distribution demonstrated at 15% O_2 and lower, with almost invisible flame.
- 80–90% NO reduction demonstrated at oxygen concentration of 15% in the mixture.

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ABSTRACT

Colorless Distributed Combustion (CDC) has shown ultra-low emissions and enhanced performance of simulated gas turbine combustors. To achieve distributed combustion, the flowfield must be tailored for desirable mixture preparation within the combustor prior to mixture ignition. Though CDC have been extensively studied using a variety of geometries, heat release intensities, and fuels, the role of internally recirculated hot reactive gases needs to be further investigated and quantified to obtain the minimum requirement of internal entrainment for achieving distributed reaction condition. In this paper, the impact of internal entrainment of product gases on flame structure and behavior is investigated with focus on fostering distributed combustion and to provide guidelines for seeking distributed combustion. To simulate the recirculated gases from within the combustor, a mixture of nitrogen and carbon dioxide is introduced to the air stream prior to mixing with fuel and combustion. Increase in the amounts of nitrogen and carbon dioxide (simulating increased recirculation) increased the reaction volume to occupy larger volume with an overall enhanced and uniform distribution as revealed from the OH* chemiluminescence intensity. At the same time, the bluish flame is replaced with a more uniform almost invisible bluish flame. The increased recirculation also decreased the NO emission significantly for the same amount of fuel burned. Lowering oxygen concentration from 21% to 15% (due to increased recirculation) 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 demonstrated for a range of recirculated gases temperature. The reaction distribution was significantly enhanced with ultra-low emissions for oxygen concentration lower than 16% setting a minimum recirculation requirement for distributed combustion.

1. Introduction

The increased role of natural gas and shale gas in electricity and power generation for energy sustainability 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 energy sources. These combustion systems need to comply with the increasingly stringent emissions regulation and form a pivotal part of the quest for environmentally friendly energy systems. These combustion systems shall achieve near zero emission of pollutants (such as, NO_x, CO, unburned hydrocarbons and soot) from the enhanced thermal field uniformity and also prevent local burnout and downtime of the equipment. 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 improved pattern factor (enhanced thermal field uniformity in the entire combustor). Reduced noise and stable combustion have also been shown for CDC conditions. The flames in distributed combustion do not show any visible flame signatures so that the flame so formed is termed

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* Corresponding author. Tel.: +1 301 405 5276; fax: +1 301 314 9477.
E-mail address: akgupta@umd.edu (A.K. Gupta).

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colorless due to negligible visible emission as compared to conventional flames.

Colorless distributed combustion (CDC) is focused on high intensity and high performance 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 requirements to achieve distributed reactions are controlled and rapid mixing between fresh reactants and hot recirculated 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 but also 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 recirculated 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 so as to increase the temperature of the reactant mixture to a level higher than the 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 preheated to 600 K to simulate gas turbine combustor inlet temperature conditions. 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 determine more precise information on of the amounts of hot reactive species required 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 temperature 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] with experiments performed at those two oxygen concentration.

Other researchers have 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 load with EGR is an acceptable condition up to 30% EGR, in the absence of acoustic instabilities and with good combustion efficiency [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 about 8% 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 recirculation/oxygen concentration). A swirl burner is used in this investigation with focus on measuring emissions (NO and CO) and flame behavior for different amounts of recirculation. 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. Approach

Recirculation of hot product gases is the main tool to achieve low oxygen concentration with high temperature environment prior to ignition to control the reaction rate. The global reaction rate for methane air combustion is expressed as a function of temperature (T), methane concentration (CH_4), and oxygen concentration (O_2) [13]:

$$R = 10^\wedge A1 * [CH_4]^\wedge B1 * [O_2]^\wedge C1 * \mathrm{Exp}[D1/T] \tag{1}$$

where the constants $A1$ varied between 8.48 and 11.7, $B1$ varied between -0.3 and 1, $C1$ varied between 0.8 and 1.3, and $D1$ varied between $-12{,}019$ and $-24{,}358$, each having the units of kmoles, cubic meters, seconds and Kelvin, respectively. Nicol et al gave a summary of these constants and their values were based on the work of different investigators [13]. Decrease in oxygen concentration, achieved through recirculation of hot reactive species, lowers the reaction rate, which can be countered by higher mixture temperatures, leading to favorable distributed combustion condition. Also, decreasing the oxygen concentration in the mixture increases the ignition delay time [14], allowing for longer mixing time prior to ignition.

The recirculated gases consist mainly of nitrogen, carbon dioxide, water vapor, and excess oxygen (depending on the stoichiometry of the reaction). To simulate the impact of recirculation of reactive product gases on the combustion process, nitrogen and carbon dioxide are introduced with the fresh mixture, with a focus to determine oxygen concentration at which distributed combustion can be fostered. Based on this required oxygen concentration and the combustor design equivalence ratio, a hot reactive gas recirculation ratio can be determined (taking into account the amount of excess oxygen recirculated).

Nitrogen and carbon dioxide were selected as they form the majority of the product gases. They were mixed in a 90% N_2–10% CO_2 by volume simulating product gases near stoichiometry conditions. Though this ratio changes as the equivalence ratio becomes leaner, the diluting gases mixture (90–10%) was kept constant for all the investigations reported here. This deviation from the actual gases 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