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Internal entrainment effects on high intensity distributed combustion using non-intrusive diagnostics

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.
- Local equivalence ratio distribution obtained through OH* and CH* chemiluminescence.
- NO chemiluminescence significantly reduced under distributed combustion conditions.
- Reaction distribution demonstrated at 15% O_2 and lower, with almost invisible flame.

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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.

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 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

* 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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[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 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 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 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 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 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 this 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 11,700 and 23,300. 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