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Fuel property effects on distributed combustion

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HIGHLIGHTS

- Examined the impact of fuel type on seeking volume distributed combustion.
- Increase in gas entrainment and decrease in O_2 conc. fostered distributed combustion.
- Examined methane, propane, and hydrogen enriched methane flames.
- Distributed combustion resulted in ultra-low emissions for all the fuels examined.
- Relation predicting distributed combustion conditions is proposed for fuels examined.

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ABSTRACT

Colorless Distributed Combustion (CDC) has been shown to provide benefits on ultra-low pollutants emission, enhanced stability and thermal field uniformity. The impact of fuel type (methane, propane, and hydrogen enriched methane) on achieving distributed combustion is investigated. A mixture of nitrogen and carbon dioxide was mixed, at different temperatures, with the normal air upstream of the combustor to simulate the hot recirculated gases. Increasing the amounts of nitrogen and carbon dioxide reduced the oxygen concentration within the combustor. Distributed combustion was identified through OH^* chemiluminescence distribution across the combustor. For methane, this oxygen concentration varied between 13.8% and 11.2% (depending on the mixture temperature) with 85% reduction in NO emissions as compared to that without entrainment. Similar behavior was demonstrated with propane and hydrogen enriched methane, albeit at a lower oxygen concentration (13.7–11.6% and 12.2–10.5%), to result in 94% and 92% reduction in NO emission, respectively. The mixed gases temperature was varied between 300 K and 750 K. Experimental data using a variety of fuels showed NO emissions of 1 PPM or less. Analysis and extrapolation of obtained data suggest that distributed combustion can be achieved at an oxygen concentration of 9.5% for hot reactive entrained gases having a temperature of 1800 K. This value may be used as a guideline to achieve distributed combustion with ultra-low emission.

1. Introduction

The increased energy concerns in terms of energy supply and energy impact on the environment have motivated energy and combustion researchers to look into novel methods to furnish our energy needs in a sustainable way with minimal impact on the environment. Combustion engineers have focused their research efforts on developing new techniques that minimize pollutants emission (such as, nitrogen oxides, carbon monoxide, unburned hydrocarbon, and soot), while maintaining high conversion (combustion) efficiency. Other important performance elements include alleviation of combustion instabilities, enhanced thermal field uniformity (pattern factor) and reduced combustion noise from the combustor. To this end, multiple combustion technologies have emerged that address the above concerns. Amongst the most promising technologies are colorless distributed combustion (CDC) [1–3]. Other technologies of flameless oxidation (FLOX) [4,5] and moderate or intense low-oxygen dilution (MILD) [6] have also emerged. Colorless distributed combustion (CDC) has presented itself as a new combustion method of high intensity combustion that offers ultra-low emission, high combustion efficiency, high combustion stability, and enhanced thermal field uniformity. These features are suitable in gas turbine combustion applications. CDC shares some of the same 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 [7]. In HiTAC, low

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oxygen concentration air, preheated to high temperatures, is used for combustion. The temperature of combustion gases in the furnace is about 50–100 °C higher than that of the preheated low oxygen concentration fuel–air just prior to ignition. The low oxygen concentration in the incoming combustion (only about 2–5% by volume) can be achieved, among other methods, through the internal recirculation of combustion gases, which also increases the air temperature [7]. In CDC, decrease in oxygen concentration and increase in temperature of 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 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 and presence of 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 of the reactants, and maintained by the increase in temperature of the reactants (both of which can be achieved through 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 helps to mitigate thermal NOx formation and emission from the Zeldovich thermal mechanism [8]. The benefits of distributed combustion have been demonstrated using a variety of geometries [1–3], temperature and pressures [2,9], and injection methods [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 has not been addressed. This critical entrainment amount was investigated in a swirl burner with focus on determining the oxygen concentration at which distributed reaction occurs [12]. This work showed that distributed reaction occurs at an oxygen concentration of about 14.5% with the reactants introduced at room temperature. For that investigation, methane was used as the fuel [12]. The investigation outlined that the reduction in emission is because of the oxygen concentration reduction rather than dilution of the gases. This was further confirmed by performing experiments under no dilution, air dilution (lower equivalence ratio) and N_2–CO_2 dilution (lower oxygen concentration) conditions. Reynold's number was kept constant to eliminate velocity change effects. Lowering oxygen concentration demonstrated lower emission as compared to adding more air. In addition, distributed combustion was only evident in the lower oxygen concentration case while air dilution showed a consistent swirl structure [13]. In this paper, the impact of fuel type on the conditions at which distributed combustion zone is achieved is investigated. If the fuel type has minimal impact on distributed combustion conditions requirement, then one can design the combustor to achieve a certain entrainment amount that satisfies these requirements leading to a fuel flexible distributed combustion operation along with all its demonstrated benefits. The examined fuels are methane, propane, and hydrogen enriched methane. Methane is the main component of natural gas which is gaining significant attention for clean energy production (as compared to other fossil fuels) with the added discoveries of shale gas. Propane was chosen as a representative of heavier hydrocarbons with potential development for liquid fuels. In addition, propane is a key component of liquefied petroleum gas, which is being used for energy applications. Methane enrichment with hydrogen allows for stable combustion at ultra-lean conditions, minimize pollutants emission, including thermal NO_x, CO and UHC with relevance to lean operation of gas turbines.

2. Fuels examined and their properties

2.1. Methane

Methane is the main component of natural gas (90% or more) which is heavily used in stationary gas turbines for electricity and power generation. The use of natural gas has been fostered by its availability through recent additional discoveries and vast amounts of shale gas reserves. Natural gas also provides the benefit of emitting less carbon dioxide per kilowatt hour of electricity as compared to other fuels (almost half that of coal, ~1200 lb/MW h for natural gas versus 2100 lb/MW h for Coal [14]). Natural gas also emits almost no heavy metal oxides as opposed to coal. All this led to the surge in natural gas use for electricity and power generation. The combustion of methane has been extensively studied. 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) [15]:

$$R = 10^{A1} \times [CH_4]^{B1} \times [O_2]^{B1} \times \mathrm{Exp}[D1/T] \quad (1)$$

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, all having the units of kmoles/cubic meters, seconds and Kelvin. Nicol et al. gave a summary of these constants and their values were based on the work of different investigators [15].

2.2. Propane

Propane is considered to be the simplest hydrocarbon whose combustion characteristics are closer to the heavier and more complex hydrocarbon fuels [16]. Consequently, propane can be used as an indicator for heavier hydrocarbons behavior in the combustor. In addition, propane is used in various applications as liquid petroleum gas (LPG) in domestic, industrial and transportation sectors.

2.3. Hydrogen enriched methane

Hydrogen enriched methane has shown considerable promise for ultra-lean premixed combustion for low emissions of NO_x. This is attributed to the lower overall equivalence ratio at which the flame can be sustained, resulting in lower temperatures in the combustion zone. However, ultra-lean flames are susceptible to local flame extinction and quenching, leading to undesirable flame characteristics, such as, flame quenching, poor combustion efficiency and acoustic combustion instabilities. The enhanced lean flame stability allows stable ultra-lean combustion without any adverse effect on increased emissions of CO, UHC and soot. Even though the addition of hydrogen may increase NO_x emission due to higher flame temperature, this can be offset by the ability to burn at an overall leaner mixture [17,18] so that lower thermal NO_x is produced. Previous studies described the influence of hydrogen addition on flame stability and flame speed under fuel-lean condition in a swirl-stabilized flame [19]. The lean stability limit was extended significantly with the addition of hydrogen to hydrocarbon fuel in a combustor. Hydrogen enrichment to CDC combustors has shown to increase the operational range of the combustor under normal inlet air temperature with a minimal increase in emissions [20,21].

2.4. Fuel properties

2.4.1. Adiabatic flame temperature

Each of three fuels examined herein has its characteristic flame speed and adiabatic flame temperature, which will affect the combustion characteristics, including flame stability and pollutants