



Fostering distributed combustion in a swirl burner using prevaporized liquid fuels



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HIGHLIGHTS

- Examined the role of entrainment on Distributed Combustion with JP-8 and ethanol.
- 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 fostered at 9.2% O_2 and lower, with almost invisible flame.
- 95% NO_x reduction demonstrated at distributed combustion with minimal impact on CO.

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ABSTRACT

Colorless Distributed Combustion (CDC) has presented itself as an environmentally friendly combustion method with significant benefits on ultra-low emissions, uniform thermal field (pattern factor), reduced noise, mitigation of instability and enhanced flame stability. CDC requisites include controlled entrainment of hot reactive species from within the combustor and their subsequent mixing with fresh reactants to form a low-oxygen concentration high-temperature oxidizer prior to ignition. This mixture results in distributed reaction over the entire combustion volume. To date, most of the CDC research efforts have focused on gaseous fuels only. In this paper, conditions fostering distributed combustion using JP-8 and alternative ethanol fuels. Data revealed that transition to CDC can be achieved at oxygen concentration of approximately 9.5% for both the fuels. This oxygen concentration was determined based on reaction field uniformity as identified from OH^* chemiluminescence signatures. Under distributed combustion, emissions were substantially reduced by some 95% to result in NO_x emissions of less than 2 PPM with minimal impact on CO emission from both JP-8 and ethanol fuels at an equivalence ratio of 0.9, with even lower emissions at lower equivalence ratios. Combining the data obtained with liquid fuels with those from gaseous fuels revealed that, regardless of the fuel used, the oxygen concentration at which CDC prevailed can be predicted based on mixture temperature within a range of 0.75%. This knowledge enables designing a combustor to achieve CDC regardless of the fuel used. The data are useful in the design and development of fuel flexible CDC for high combustion intensity gas turbine applications.

1. Introduction

As energy awareness increase among societies, with desire for more environmentally friendly energy conversion methods, research efforts continue to focus on satisfying the energy needs with minimal impact on the environment. Although significant achievements in renewable energy have been accomplished, traditional power sources, including fossil fuels, are expected to remain a major player in the future energy conversion devices [1]. The Annual Energy Outlook predicts that the share of petroleum and other liquid fuels will remain almost constant, while natural gas' share is expected to increase [2]. This presence of

fossil fuel in the worlds energy mix have motivated combustion engineers to search for new and novel ways to convert the chemical energy stored in fuels into useful heat energy through new and novel combustion techniques. Since the 1990s, different research groups have proposed combustion methods that minimize combustion emissions while maintaining overall performance. Among these methods are rich-quench-lean burn (RQL) [3–5], flameless oxidation (FLOX) [6–8], moderate or intense low oxygen dilution (MILD) [9–11], and colorless distributed combustion (CDC) [12,13].

Colorless Distributed Combustion (CDC), which is the focus of this paper, is based on the concept of HiTAC [14], wherein low oxygen

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concentration air preheated to high temperatures, is used for combustion. The use of this hot diluted oxidizer has demonstrated that the temperature of combustion gases in the furnace was only about 50–100 °C higher than that of the preheated low oxygen concentration air just prior to ignition. In CDC, the low oxygen concentration high temperature oxidizer is achieved through entrainment and recirculation of hot reactive species from within the combustor and their subsequent mixing with the freshly introduced air. Providing adequate entrainment and mixing prior to ignition was shown to be critical to achieve distributed reaction combustion. As distributed reactions were achieved, a lower reaction rate was attained over the entire volume of the combustor, as opposed to the concentrated thin reaction flame front with high reaction rates that also produce local hot spots. This distribution over a larger volume results in the same fuel consumption, as that of concentrated flame fronts, with lower temperature rise in the combustor. The low reaction rates were achieved through lowering of the oxygen concentration in the reactants, and increased temperature of the reactants, which was achieved simultaneously through the entrainment of hot reactive gases from within the combustor.

CDC not only helps avoid the formation of thin reaction zone but also mitigates the formation of hot-spots in the flame that help minimize thermal NO_x formation and emission from the Zeldovich thermal mechanism [15]. The benefits of distributed combustion in terms of pollutants emission have been demonstrated using a variety of geometries, temperatures, pressures, and injection methods [12,13,16,17]. Moreover, the conditions required to achieve CDC have been investigated in detail, with focus on the oxygen concentration required to foster distributed combustion [18]. The role of various input and operational parameters (oxygen concentration, temperature, and global equivalence ratio) on thermal field and local equivalence ratio uniformity were examined [19,20], and the different flame behavior from the flame-flow interaction along with the role of integral length scale and flame thickness on distributed combustion [21] have been investigated. However, these investigations focused on methane [18–21], propane and hydrogen enriched methane [22] as the fuel.

With the increased demand in power and propulsion for gas turbines that operate on liquid fuels, we focus our efforts to investigate the conditions that foster CDC with liquid fuels. Achieving low emissions with liquid fuels have been examined by different groups that has been called MILD and Flameless Combustion [23–25]. In their work, Ye et al. examined prevaporized ethanol, acetone, and heptane in a reverse flow combustor, wherein they found that ethanol burns well under MILD conditions while acetone and heptane demonstrated some instabilities [24]. Reddy et al. showed that achieving flameless combustion with liquid fuels at ambient conditions is possible in a preliminary study using a two-stage combustor [25]. However, sometimes operating with premixed and prevaporized fuel can induce instabilities. These studies used phase-averaged particle image velocimetry (PIV) that outlined a range of equivalence ratio in the TAPS (twin annular premixed swirl) combustor that could operate without entering a “growl” regime [26]. To enhance liquid fuel stability, it was suggested to add hydrogen to JP-8 flame, leading to stabilizing the flame, and reducing the flame lift off. The authors suggested hydrogen addition as an effective way to reduce unburned hydrocarbons as well [27]. Focus on JP-8 combustion was not only limited to combustion in gas turbines, but extended to include laminar burning speeds at high temperature and pressures as well as with diluents [28,29]. JP-8 performance with diluents is critical to understand the possibility of achieving CDC with liquid fuels. The authors concluded that laminar burning speeds of JP-8 increased with increase in temperature and decreased with increase in pressure [28]. They also found that addition of diluents did not had a major effect on stability but decreased the laminar burning speeds due to decreased adiabatic flame temperature [29]. This behavior of lower flame speeds upon dilution is favorable to achieve CDC [21].

Liquid fuel interests are not only limited to JP-8. Bio-fuels are also of interest as they offer a good viable solution for the continuous decrease

in fossil-fuel reserves as well as the environmental concerns about carbon emission. The term bio-fuel is referred to fuels produced from bio-materials, such as, biomass and wastes. Such fuels include, but not limited to, bio-methanol, bio-ethanol, bio-diesel pyrolysis oil, biogas, synthetic gas, and hydrogen [30].

Ethanol has been examined for gas turbines applications, and the results show favorable properties as a sustainable and renewable fuel. However, due to its lower lubricity and lower heating value, some changes are required in the fuel handling system for retrofitting in gas turbines [31]. Using biofuels, as opposed to traditional fossil fuels, is carbon neutral so that its use reduces the net amount of carbon dioxide emitted into the atmosphere. Experimental and numerical studies on the combustion and oxidation of ethanol has been performed that provided numerous new data to support modeling studies on the oxidation and combustion of ethanol [32]. Ethanol has been also investigated as an alternate fuel for diesel engines [33]. Ethanol has also been studied in detail with focus on laminar burning speed and extinction properties and their dependency on temperature [34–36].

In this paper, the conditions fostering distributed combustion have been examined using liquid fuels as opposed to previous efforts that focused on gaseous fuels [22]. Focus is on the oxygen concentration at which the reaction regime transforms into volumetric distributed combustion mode along with ultra-low emissions. It is also desired to compare the performance of liquid fuels with gaseous fuels to assess the fuel flexibility in distributed combustion. The primary focus is on determining if the role of fuel has any impact on the oxygen concentration at which distributed combustion occurs.

2. Experimental facility

The experiments were performed using a swirl burner. Details of this swirl burner can be found elsewhere [37]. Different amounts of nitrogen and carbon dioxide (mixed in a 90%–10% ratio by volume) were mixed with air upstream of the burner, thus simulating product gas entrainment with lower oxygen concentration in the mixture prior to ignition. To start the burner, methane was injected in the air line. Once the burner was stabilized, the fuel was gradually switched to liquid fuel (as vapors) until the burner completely operated with the liquid fuel. To control the gases, differential pressure laminar flow controllers were used with an uncertainty of 0.2% of full scale + 0.8% of set point for air and Nitrogen. Thermo-gravimetric flow controllers were used for other gases, with uncertainty of 1% of full scale (methane for startup), and 1.5% of full scale (carbon dioxide). For liquid fuels, a liquid fuel positive displacement pump (VICI M50) was used to furnish the required flowrates with a precision of ± 0.5%.

It is to be noted that both fuels examined, JP-8 and ethanol, have a much higher laminar flame velocity as compared to that of methane [38]. This can cause instabilities as the swirl burner used in the experiments was designed for gaseous fuels. The liquid fuel was prevaporized and this fuel will have a large density as compared to the gaseous fuel leading to lower flow velocities across the injection holes. This low injection velocity, coupled with the higher burning velocity of the liquid fuels at higher temperatures as they were injected prevaporized, resulted in more propensity to flashback towards the injection location. This scenario will lead to flame oscillation between the injection point and the swirler downstream which was to be avoided.

This instability was mitigated by adding carbon dioxide to the liquid fuel line that effectively increased the flow velocity through the liquid fuel injection ports, and helped stabilize the flame. Carbon dioxide addition also helped to mitigate any coking or cracking of the liquid fuels. The added carbon dioxide to the fuel line increased the flow velocity significantly in the fuel feed lines, lowering the residence time in the lines, to less than 1 s. This minimized any thermal decomposition. Widegren et al. showed that for 1% of the fuel (Jet A, which is similar to JP-8) to decompose at 450 °C, the residence time shall be less than 1 min [39], with similar results shown by others at 375 °C [40].

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