Fuel 143 (2015) 334–342

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Impact of pressure on high intensity colorless distributed combustion

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

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

HIGHLIGHTS

- Examined the impact of pressure on performance in distributed combustion.
- Lower velocity at higher density and pressure results in inadequate mixing.
- NO increased and CO decreased with pressure and residence time.
- NO increased marginally with increase in pressure at given residence time.
- Ultra-low emissions at high pressures under distributed combustion condition.

ARTICLE INFO

Article history:
Received 25 September 2014
Received in revised form 16 November 2014
Accepted 17 November 2014
Available online 27 November 2014

Keywords:
Colorless distributed combustion (CDC)
Ultra-low NO_x and CO emission
Gas turbine combustion
Elevated pressure operation

ABSTRACT

In recent years, colorless distributed combustion (CDC) has been shown to provide ultra-low pollutants emission, enhanced stability, fuel flexibility and thermal field uniformity. To achieve CDC conditions, fuel–air mixture must be properly prepared prior to the mixture ignition. In this paper, the impact of moderate pressure increase on a test combustor is examined with emphasis on pollutants emission under near CDC conditions. Increase in pressure at constant mass flow rate resulted in a significant increase in NO emission and departure from CDC conditions. This is a result of reduction of the volume flow rate and injection velocity with pressure increase, as well as an increase in the apparent residence time of gases within the combustor. These conditions led to less than adequate mixing and more residence time of gases in the post flame zone to form NO_x. CO emissions were reduced as longer residence time allowed for complete conversion of CO to CO_2. Also, the increase in pressure enhanced chemical kinetics and suppressed dissociation. Increasing the combustor pressure with constant heat release intensity, where mass flow rates are increased to keep the apparent residence time constant, showed a slight increase (1 PPM) of NO under premixed conditions and significant reduction of CO. OH^* chemiluminescence showed that the reaction zone did not change with increase in pressure under premixed combustion. For non-premixed combustion, the reaction zone intensity increased and was more concentrated with increase in pressure to result in higher emissions as compared to the premixed case. In both cases, CO emission was significantly reduced due to the increased heat load and temperatures within the combustor. Relations describing change of NO and CO emissions with pressure were used to predict the combustor emissions at higher pressures. Difference between premixed and non-premixed modes revealed the need for more adequate mixing, necessary for CDC condition. Increase in pressure without considering flow velocities and flowfield can lead to departure from CDC conditions with simultaneous increase in emissions.

1. Introduction

Increased concern on future energy in terms of energy security and environmental impact have motivated engineers to look for new and novel methods to furnish our energy needs in a sustainable way with minimal impact on the environment. In this aspect, combustion engineers have focused on finding new combustion techniques that minimize pollutants emission (such as oxides of nitrogen, carbon monoxide, unburned hydrocarbon, and soot), and develop fuel flexibility for combustors using fossil fuels and renewable biofuels, while maintaining high conversion (combustion) efficiency. Other important performance factors include alleviation of combustion instability, enhance thermal field uniformity (pattern factor), and reduce combustion noise and pressure drop across the combustor. In recent years, multiple new combustion

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

http://dx.doi.org/10.1016/j.fuel.2014.11.061
0016-2361/

technologies have emerged that address the above concerns on performance. Amongst the most promising technologies are colorless distributed combustion (CDC) [1–3], flameless oxidation (FLOX) [4,5], and moderate or intense low-oxygen dilution (MILD) [6]. From these technologies, colorless distributed combustion (CDC) has presented itself as a new combustion method that offers ultra-low emission, high combustion efficiency, high combustion stability, and enhanced thermal field uniformity. CDC incorporates 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 furnace application [7]. In HiTAC, low oxygen concentration air at normal temperature is used for combustion with the air preheated to high temperatures prior to the ignition of fuel. The temperature of combustion gases in the furnace is only about 50–100 °C higher than that of the preheated low oxygen concentration air just prior to ignition. The oxygen concentration in the incoming combustion air is generally very low (only about 2–5% by volume, depending on the application). Increase in incoming air temperature has been achieved through enthalpy exchange with the hot exit gases or via internal enthalpy exchange [7]. In CDC, increase in temperature of the fresh mixture stream is achieved through internal recirculation of hot reactive species from within the combustor. This internal recirculation not only increases the fresh reactants temperature but also decreases oxygen concentration to result in low oxygen high temperature mixture prior to ignition and combustion of the fuel. This combination of high temperature and low oxygen concentration results in a distributed reaction, wherein the reaction zone occupies a larger volume at a lower reaction rate (from high temperature of the reactants). This low reaction rate over large reaction volume results in the same fuel consumption and reaction as normal combustion. However the benefits include combustor operation at lower equivalence ratios, low temperature rise, and elimination of thermal non-uniformities. This design method helps to mitigate thermal NO_x formation and emission produced from the Zeldovich thermal mechanism [8].

Adequate and fast mixing between the fresh reactants and recirculated hot reactive species is critical to achieve distributed combustion conditions. Different geometries have been investigated including swirling and non-swirling configurations with focus on pollutants emission [1] and isothermal flowfield [9]. Swirling combustor geometry that demonstrated the lowest NO and CO emissions also had the highest recirculation ratio in the geometries examined [9]. These conditions have established the impact of internal recirculation of hot reactive species on seeking designs for ultra-low emissions. Swirling motion was generated through tangential air entry rather than swirlers. Different air and fuel introduction scenarios have been investigated to enhance the combustion performance and foster CDC conditions. Increased air injection velocity revealed an increase in internal hot reactive species recirculation and a decrease of pollutants emission [10]. Different fuel introduction schemes have been examined with focus on mixture preparation effects prior to ignition [11]. Mixing air, fuel, and hot reactive species is challenging especially under non-premixed conditions where air and fuel are introduced separately. The difference between cross injection and co-axial injection was investigated [11] along with the increased separation between air and fuel injection points in cross flow configuration [1,11]. Early injection resulted in air and fuel ignition without proper mixing with recirculated gases while late injection led to ignition without adequate fuel–air mixing [11], leading to a diffusion flame behavior [1]. These two extremes conditions of early and late injection can lead to significant increase in emissions, specifically NO emissions, which can be avoided through proper separation between air and fuel injection location in non-premixed combustion mode [11]. Non-premixed conditions are favorable for alleviating combustion instability. The CDC mode of combustion has been shown to alleviate combustion instability under both non-premixed and premixed combustion condition.

CDC have been extensively studied under atmospheric pressure conditions using room temperature air [1,9–10], as well as preheated air [2,11]. Various fuels examined include methane [1,2], ethanol, propane and kerosene [12], and biofuels [13]. Gas turbines combustors operate at elevated pressures and temperatures (due to heating through the compressor). The impact of inlet temperature have been studied up to 600 K (corresponding to a pressure ratio ∼16), where the air inlet temperature was shown to significantly impact NO emissions [2]. However, limited data is available on CDC operation under elevated pressure conditions. Combustor operation at elevated pressure is expected to impact the reaction behavior, flowfield, residence time of gases and pollutants emission.

The impact of pressure on NO_x emissions have been numerically investigated and compared to experimental values under lean premixed conditions [14]. Rutar and Malte [14] and Steele et al. [15] found that NO_x slightly decreases with increase in pressure at constant residence time. However, NO_x, increased significantly with increase in residence time (higher than 1.5 ms) for all pressures examined. This increase in NO_x was accompanied with a sharp decrease in CO emission. Other researchers have demonstrated the impact of pressure on NO_x emission, where emissions increased with increase of pressure at low temperature (lean/rich combustion) and decreased at high temperature (near stoichiometric conditions) [16]. They also investigated the impact of unmixedness on emissions (as a result of partially premixed combustion, or departure from perfectly premixed combustion). The unmixedness (U, defined as: $f'^2/[f(1-f)]$, where f' is the fluctuation of the fuel concentration, and f is the mean fuel concentration) takes a value of zero for perfectly premixed condition and one for a perfectly unmixed injection [16,17]. The authors concluded that under perfectly premixed conditions, NO_x emission have a negative pressure exponent. However, for unmixedness levels typical of gas turbine combustors, NO_x emissions have a positive pressure exponent [16]. This investigation was limited to unmixedness of about 0.08%. Unmixedness has been also investigated under simulated gas turbine conditions, where experimentally measured NO_x emissions increased with both pressure and degree of unmixedness (up to 0.3% unmixedness) [17].

In this paper, the impact of pressure on NO and CO emissions is examined in a model combustor at an energy (heat) release intensity of 31.5 MW/m^3 atm that have relevance for stationary gas turbine applications using methane as the fuel. The impact of increase in pressure on pollutants emission is investigated. The experiments were performed while keeping the flow rates constant (thus increase of residence time). The effect of increase in pressure and flow rates (keeping the residence time constant) on pollutants emission is also examined. The results are reported under both premixed and non-premixed combustion modes with an effort to outline the combustor performance at elevated pressures. Combustor pressures were varied between 1 and 2.5 atm with view to develop a high pressure combustor for further experimentation at much higher pressures suitable for gas turbine conditions.

2. Experimental facility

The combustor performance under elevated pressure conditions was evaluated with focus on pollutants emission. The combustion chamber utilized was a cylindrical chamber with air injected tangentially at half the height of the chamber for all the cases investigated. For enhancing the residence of reactants in the combustor, a tube was extended inside the combustor for product gas exit. Fig. 1 shows a schematic diagram of the combustor used. This extended