Fuel 186 (2016) 248–260

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Fuel injection effects on distribution reaction in a high intensity combustor

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HIGHLIGHTS

- Colorless distributed combustion.
- Dual location fuel injection.
- NO^*-OH^* chemiluminescence.
- Ultra-low NO-CO emissions.

ARTICLE INFO

Article history:
Received 5 July 2016
Received in revised form 7 August 2016
Accepted 15 August 2016
Available online 27 August 2016

Keywords:
CDC
Dual location fuel injection
NO^*-OH^* chemiluminescence

ABSTRACT

The role of dual location fuel injection (versus single injection) is examined for improved mixture preparation with enhanced reaction distribution in the combustor that offers reduced emissions. A cylindrical combustor was used at a combustion intensity of 36 MW/m^3 atm and heat load of 6.25 kW. Three different configurations were examined for the effect of dual location fuel injection using methane as the fuel. NO reduction of 48% was achieved with fuel injected at two locations versus single location at an overall equivalence ratio of 0.7. The OH^* Chemiluminescence intensity distribution with dual location fuel injection showed the reaction zone to shift further downstream that provided longer fuel mixture preparation time prior to ignition under favorable fuel distribution conditions. The longer mixing time helped to improve mixture preparation with lower emissions. The NO^* chemiluminescence signatures supported the results obtained on reduced NO emission. Mean to maximum OH^* signal showed that dual location fuel injection enhanced distributed reaction at certain fuel distributions between the two locations (fuel injection ratio lower than 70%) for all the three configurations examined. Increase in air injection velocity from 46 m/s to 102 m/s showed up to 85% NO reduction utilizing dual location fuel injection without any increase in CO emission. Increase in air preheats from 300 K to 600 K reduced the extent of NO reduction. Dual location fuel injection provided improved reaction zone distribution in the combustor for all the experimental conditions reported here. Correlations are provided that describes the NO_X emission as function of fuel injection ratio.

1. Introduction

Stationary gas turbines are used worldwide for electricity production due to their higher performance and reduced emission. However, environmental regulations recommend achieving ultra-low emission levels from all combustion process. Novel combustion strategies are required to reduce emission of harmful pollutants. Natural gas operated power generation plants are more favorable than other fossil fuel fired power generation. Nitrogen oxides (NO_X) are produced from the burning of fuels in gas turbine power plants. NO_X affects human health, cause acid rain and photochemical smog. It reacts with ammonia and moisture forming nitric acid and related particles. Carbon monoxide is produced from incomplete combustion. Significant progress has been made to mitigate nitric oxide (NO) and carbon monoxide (CO) formation and emission. Efficient natural gas power plant results in almost 50–60% less CO_2 emission than a typical coal burning power plants. CO_2 is a greenhouse gas that causes global warming with primary source being the combustion of fossil fuel in power plants.

The thermal field uniformity throughout the combustion zone is a key factor to mitigate NO_X and other pollutants emission.

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http://dx.doi.org/10.1016/j.fuel.2016.08.070
0016-2361/

Nomenclature

CDC	colorless distributed combustion
Ø	total equivalence ratio
FIR	fuel injection ratio is defined as the amount of fuel to an injector to the total amount of fuel to the combustor was used $FIR = \frac{F_i}{\sum_i^N F_i}$ where Fi represents fuel flow rate through injector (i)
V_{air}	Air velocity
OR	operational range is defined as the range of minimum to maximum fuel injection ratio operating range of FIR in which the emissions concentrations are lower than (single injection) 100% FIR's emissions concentrations
$Ø_s$	secondary equivalence ratio
a.u	arbitrary unit
T_{air}	air injection temperature
$NO_{min.}$	it is minimum corrected NO (corrected at 15% O_2) achieved by dual location fuel injection configuration
NO_{single}	it is the corrected NO (corrected at 15% O_2) concentration achieved by single location fuel injection configuration at FIR 100%

Avoidance of the local hot spots within the combustion chamber help enhance the life time of the engine. To reduce the NO_X, CO, soot and unburned hydrocarbons, mixing between air and fuel must be enhanced prior to the mixture ignition. A promising strategy to provide ultra-low emissions and better combustion specification for gas turbine combustors is colorless distributed combustion (CDC). The CDC has shown uniformly distributed reaction region throughout the entire combustion zone with ultra-low emission (near zero concentrations) [1–6]. The CDC shares similarities with high temperature air combustion (HiTAC) [6] except for the very short residence time available in CDC and significantly higher thermal intensities. The reactive gases with high thermal energy are internally entrained and mixed with air inside the combustor. Entrainment of hot reactive gases from within the combustor dilutes the oxygen concentration and increases the oxidizer temperature that allows avoidance of peak flame temperatures (hot spots) in the combustion zone and reduces the thermal NO_X formation. The CDC incorporates unique mixing of hot reactive gases with the air and/or fuel to improve thermal field uniformity. Besides, CDC provides low noise stable combustion without any need for flame stabilizers. In distributed combustion, the flame signatures are invisible as compared to conventional flame (hence colorless distributed combustion, CDC) and the reaction zone is distributed.

Ignition, wide burning range, high combustion efficiency, and low pollutants emission are some of issues that must be considered with single fuel injection combustion in gas turbines. Therefore, multiple different strategies have been developed to achieve low NO_X emission. Hot gases entrainment has shown to introduce ultra-low emissions and high combustion efficiency. This entrainment and the subsequent mixing occurring just prior to ignition are substantial components to foster distributed reactions. Distributed reaction is characterized by a lower reaction rate throughout the entire combustion volume which reduces the temperature rise. In contrast normal flames have concentrated flame reaction front with higher reaction rate that result in local hot spots and high NO_X emission. Enhanced mixing between the hot gases and air dilutes the oxygen concentration to result in lower reaction rate. Distributed reaction avoids thin reaction zone and results in a uniform temperature distribution which mitigates thermal NO_X formed from the Zeldovich mechanism (thermal NO_X mechanism) [7–13].

Multipoint injection promotes uniform mixture distribution, and a small multi-zone burning provides shorter burning time, both resulting in reduced NOX formation [14]. Moreover, multi-location fuel injection is expected to provide far more uniform distributed reaction zone in the combustors and reduced emissions. Multi-location fuel injection is expected to improve mixing prior to ignition. The mixing strategy between air and fuel jets in cross flow has a substantial role to reduce overall emissions in both can and annular type gas turbine combustors [14,15] wherein jet in cross flow mixing is used. Several investigations have been performed on the cross flow mixing of air jets into hot jets that form the fuel-rich primary zone due to its wider range of applicability, such as in gas turbine combustors [14,15]. For confined combustion the degree of mixing is affected by geometry of the jets and cross flow, jet-to-mainstream density and momentum-flux ratios. In confined subsonic cross flow, the primary interest has been on the jet-to-mainstream momentum flux ratio and this ratio must be determined [14]. The Rich-burn/Quick-mix/Lean-burn (RQL) combustor has been proposed to minimize the formation of oxides of nitrogen (NO_X) in gas turbine combustors. The goal here is to rapidly convert the overall fuel-rich mixture to fuel-lean mixture, thus avoiding near stoichiometric combustion and minimize NO_X formation that results from high temperatures [14,15].

Previous investigations have been performed on (RQL) combustor to study the effect of mixing rich fuel main stream with penetrating jets. Authors [14] used a cylindrical reactors and different numbers of penetrating jets (8, 12, 14 and 22). The experiments performed under non-preheating and preheating conditions showed that the NO_X concentrations in the center region for the 8-hole module were significantly lower than that from the other three modules due to good penetrations achieved with the 8-hole module case. High concentrations of NO_X were observed in the wake of the jets near to the cylinder walls. This was attributed to high temperatures and longer residence times caused by jet induced recirculation [14]. Confined mixing between air and fuel (propane) [16] was studied in a cylindrical combustor, using 10 round orifices attached to the combustor side walls. The temperature and emissions were recorded upstream using different number of injectors [16]. A lean-direct injection (LDI) has been used wherein the fuel was injected directly into the combustion zone at overall lean equivalence ratio mixtures. A multi-injection mode was used that had 49 injectors (having the same equivalent size as that of a single injector [17]. The results from the multiplex NO_X emission was compared with the Multi Point Integrated Module (MPIM) [17,18] obtained in a previous study. The results from the 49 multiplex showed approximately the same NO_X levels as that obtained from the 25 point MPIM combustor. However, the NO_X levels were higher using the 36 point MPIM [17]. In staged combustion, methane/air flames were investigated for the effects of pressure, flame temperature, fuel-to-air ratio and fuel staging ratio since these parameters have a major effect on NO_X formation [19]. The effect of different pilot [20] injection configuration on flame stability, emission and flame location were inspected using swirl burner. Different secondary injection (pilot fuel, premixing of pilot fuel with air, air injection only) were examined for different