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Toward ultra-low emission distributed combustion with fuel air dilution

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HIGHLIGHTS

- Examined dilution of fuel and air for ultra-low emission in distributed combustion.
- Effect of air and fuel streams mixed outside the flammability limits.
- Impact of jet momentum ratio on mixing and emission.
- Low NO and CO emission from novel non-remixed combustion.
- Alleviation of flashback or instability in distributed combustion.

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ABSTRACT

Colorless distributed combustion (CDC) has been shown to offer enhanced combustor performance for stationary gas turbine application with near zero emissions, high combustion intensity and efficiency, thermal field uniformity, and enhanced stability. Mixture preparation to form hot and low oxygen concentration environment paves the path to achieve CDC conditions. In this paper, a new approach of air dilution in partially premixed combustion conditions is employed and the results compared to premixed and non-premixed injection of air and fuel. Portion of the fuel is introduced in the air stream and portion of the air is introduced in the fuel stream such that the local equivalence ratios for each stream is well outside the flammability limit to eliminate flashback and instabilities. The experimental data demonstrated ultra-low emissions with this injection scheme. At equivalence ratio of 0.6, NO emission was 63% lower than non-premixed combustion mode. Also NO emission was similar to the premixed combustion with the advantage of eliminating flashback and flame instabilities that often prevail in premixed combustion conditions. Dilution provided 50% CO reduction as compared to non-premixed combustion. Numerical simulations, validated through Particle Image Velocimetry, were performed to outline the mixing process in each of the three cases. The methane mixture fraction prior to ignition, determined numerically, was found to be one half of that for the non-premixed case and close to that of the premixed case. This enhanced mixture preparation, associated with the new air and fuel dilution technique, resulted in reduced emission. Also the jet momentum ratio (between both streams) is enhanced, mainly due to the air addition to the fuel stream, to result in better mixing and a better reaction distribution for ultra-low emissions. Further reduction of NO_x is expected with improved distributed combustion condition.

1. Introduction

Gas turbines continue to receive increased attention as a prime source for clean electric energy production through combined cycles or through combined heat and power production. This is attributed to their high efficiency and new discovery of natural gas and shale gas resources in the states, fostering domestic energy and energy security. In addition, gas turbine is extensively used in aviation, both civilian and military, with increased interest in lowering emissions and biofuel adoption. This has motivated combustion engineers to develop new and novel combustion methods that comply with increasingly stringent regulations while reducing energy consumption. Reducing pollutants emission (such as, NO_x, CO, unburned hydrocarbons and soot) and increasing performance of gas turbine combustors continues to be of significant

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importance for environmental friendliness and energy conservation. The thermal field uniformity at the combustor exit (pattern factor) and within the combustor in gas turbines engines needs to be enhanced with the direct benefits of reducing pollutants emission (NO_x), preventing local burnout of combustors, reducing air cooling requirements for turbine blades, and increasing their lifetime. The thermal field uniformity reduces hot spot zones in the combustor, reduces cooling air requirements of turbine blades so that one can increase engine efficiency from firing at higher temperatures.

Colorless distributed combustion (CDC), which shares similar fundamental principles of high temperature air combustion (HiTAC [1]), has been investigated previously and proven itself as a novel option for near zero emissions of NO_x and CO [2–5]. CDC also offers significantly improved pattern factor, stable combustion, alleviation of combustion instabilities, low pressure drop and low noise emission for gas turbine combustion applications. This combustion method is named "colorless" as it results in negligible visible signatures from the flames as compared to conventional flames in gas turbine combustors.

Colorless distributed combustion have been shown to provide significant improvement in pattern factor, low sound emission levels and ultra-low emissions of NO_x and CO under different flow configurations conditions [2–5], using a wide variety of fuels that include gas, liquid and bio-fuels [6–8]. The critical requirement to achieve colorless distributed combustion is controlled and rapid mixing between the combustion air and/or fuel stream with hot reactive species from within the combustor so as to form a high temperature low oxygen concentration mixture. Forming this mixture forms the basis for seeking distributed combustion condition as they foster distributed reactions, wherein the reaction zone occupies a larger volume with a lower reactivity due to the lower oxygen concentration. This low reaction rate is made possible through the high temperature of reactants (due to the inclusion of hot reactive species), leading to lower temperature rise [1]. Such distributed reaction combustion results in a large reaction zone volume with low reaction rate to result in low overall temperature rise in the combustor. This is in contrast to traditional (normal, or high oxygen concentration air) combustion that results in sharp temperature rise in the concentrated thin reaction flame front. Such thin reaction zones results in hot spot zones that foster thermal NO_x emissions produced from the Zeldovich thermal mechanism [9], which is the major NO_x contributor in gas turbine engines.

The importance of mixture preparation with hot and reactive fuel–air mixture stream cannot be overstated. Such mixture requires controlled entrainment of hot reactive combustion gases into the reactants. The recirculation of hot reactive species into the fresh stream can be achieved through proper design of the combustor flowfield. Entrainment of hot reactive species have been studied under different configurations, including swirling and non-swirling flow configurations [4,10]. Swirling configuration, wherein air was injected tangentially and product gases exited axially, showed higher recirculation ratios compared to non-swirling configurations under isothermal conditions [10]. Such increased recirculation resulted in lower pollutants emission and enhanced OH^* chemiluminescence distribution within the combustor [4].

Enhanced hot reactive species recirculation and entrainment through tangential air injection provides only part of the mixing. Fuel introduction still needs to be addressed. Different fuel injection scenarios have been examined including premixed, non-premixed and coaxial-partially premixed. Different separation distances between air and fuel injection locations have been examined [2,4], with focus on pollutants emissions and reaction distribution. In another study, premixed and non-premixed injection was compared to coaxial injection with focus on ignition time. Early injection and ignition was to be avoided as the air, fuel, and hot reactive gases were not well mixed yet. On the other hand, late injection leads to spontaneous ignition of the fuel before being mixed with the hot and diluted oxidizer due to the high temperature, a condition that should be avoided [11].

To enhance mixing, air and fuel dilution with flue gasses have been studied with emphasis on the effect of air dilution versus fuel dilution on nitric oxide emissions [12]. It was concluded that fuel dilution has the greater effectiveness as compared to air dilution in practical applications due to the enhanced turbulent mixing and heat transfer. Dilution of fuel with inert gases has been investigated for combustor operation with ultra-low emission. Nitrogen addition has been shown to decrease NO emissions by 50% to achieve emissions of 2 ppm of NO and 12 ppm of CO [13]. The same trend was observed with air and carbon dioxide dilution [6]. The decrease in pollutants emission is attributed to the fuel jet having higher jet momentum (due to the added diluents). Also, the added mass acts as a thermal sink that lowers the overall combustor temperature which significantly lowers thermal NO_x through Zeldovich mechanism [9].

Fuel mixing have been extensively studied under various configurations ranging from premixed to non-premixed fuel injection, including partially premixed injection. Traditionally premixed combustion offered lower emissions as compared to non-premixed conditions. The impact of unmixedness or non-uniformities in premixed combustion have been extensively studied. In one of the studies, NO_x emissions nearly doubled with change from premixed to partially premixed configuration [14]. Also, NO_x emissions depended heavily on the mixing length and air/fuel jet Reynolds numbers. Mongia et al. [15] reported a dramatic increase of NO_x production with incomplete mixing even at lean conditions. NO_x increased 4 folds when the combustor operated with 0.0085 unmixedness (for premixed stream, unmixedness is 0, while for a non-premixed stream, this value is 1) [15]. Non-premixed combustion has been investigated in detail as well with the goal of lowering emissions and enhance mixing. One common practice used to enhance mixing, is to create recirculation and stabilize combustion using swirl flow that entrains and recirculates a portion of the hot combustion products back to the root of the flame. For such

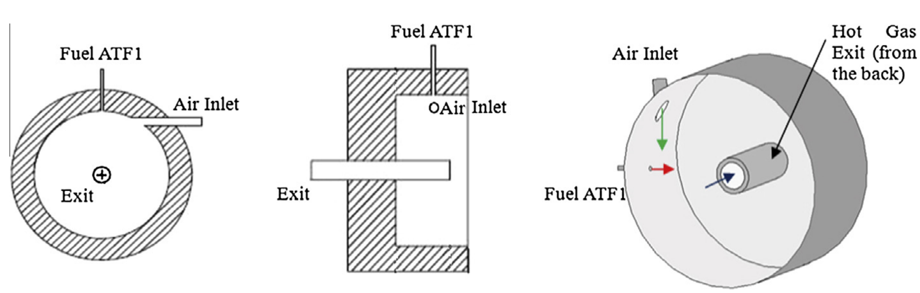

Fig. 1. Schematic diagram of the combustor used.