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Fuel flexible distributed combustion for efficient and clean gas turbine engines

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

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

HIGHLIGHTS

- Examined distributed combustion for gas turbines applications using HiTAC.
- Gaseous, liquid, conventional and bio-fuels are examined with ultra-low emissions.
- Novel design of fuel flexibility without any atomizer for liquid fuel sprays.
- Demonstrated fuel flexibility with emissions <4.5 PPM of NO for different fuels.
- Demonstrated CO emission <10 ppm for methane based fuels, <40 PPM for others.

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ABSTRACT

The need for fuel flexible ultra-low emission gas turbine combustors is imminent to secure future power needs. Distributed combustion technology is demonstrated to provide significant performance improvement of gas turbine combustors including uniform thermal field in the entire combustion chamber (improved pattern factor) at very high combustion intensity, ultra-low emission of NO_x and CO, low noise, enhanced stability, higher efficiency and alleviation of combustion instability. Distributed reaction conditions were achieved using swirl for desirable controlled mixing between the injected air, fuel and hot reactive gases from within the combustor prior to mixture ignition. In this paper, distributed combustion is further investigated using a variety of fuels. Gaseous (methane, diluted methane, hydrogen enriched methane and propane) and liquid fuels, including both traditional (kerosene) and alternate fuels (ethanol) that cover a wide range of calorific values are investigated with emphasis on pollutants emission and combustor performance with each fuel. For liquid fuels, no atomization or spray device was used. Performance evaluation with the different fuels was established to outline the flexibility of the combustor using a wide range of fuels of different composition, phase and calorific value with specific focus on ultra-low pollutants emission. Results obtained on pollutants emission and OH^* chemiluminescence for the specific fuels at various equivalence ratios are presented. Near distributed combustion conditions with less than 8 PPM of NO emission were demonstrated under novel premixed conditions for the various fuels tested at heat (energy) release intensity (HRI) of 27 MW/m^3-atm. and a rather high equivalence ratio of 0.6. Higher equivalence ratios lacked favorable distributed combustion conditions. For the same conditions, CO emission varied for each fuel; less than 10 ppm were demonstrated for methane based fuels, while heavier liquid fuels provided less than 40 ppm CO emissions. Lower emissions of NO (<4.5 PPM) were also demonstrated at lower equivalence ratios. This demonstration outlines the combustor ability for fuel flexibility without any modifications to the combustor injectors, while maintaining high performance. Further reduction of NO_x can be possible by establishing true distributed combustion condition, in particular at higher equivalence ratios.

1. Introduction

Depletion of fossil fuels and widespread concern about global warming have motivated engineers to develop novel combustion technologies using conventional and alternative fuels to power the current and future energy systems without any impact on the environment while maintaining high conversion efficiency and performance. Consequently, the necessity for a combustor that is fuel flexible and surpasses the increasingly stringent environmental regulation requirements concerning emissions from different kinds of propulsion and power systems along with quest for

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

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environmentally friendly energy systems have challenged combustion engineers to develop novel combustion techniques for achieving ultra-low levels of pollutants emission (such as, NO_x, CO, unburned hydrocarbons and soot), along with reduced noise, low flame fluctuations, alleviation of combustion instability and improved pattern factor from gas turbine combustors. Colorless distributed combustion (CDC), which shares some of the same principles of high temperature air combustion (HiTAC) [1], has been shown to provide huge potential to reduce emissions of NO_x and CO, and also provide uniform thermal field in the entire combustor (improved pattern factor) at high combustion intensity without using any flame stabilizer for flame stability. Reduced noise and stable combustion have also been shown under CDC conditions for gas turbine combustion application. The flames in distributed combustion do not show any visible signatures so that the flame so formed is termed colorless due to negligible visible emission from the flames as compared to conventional flames.

Colorless distributed combustion (CDC) investigated here is focused on high combustion intensity for stationary gas turbine combustion application. Previous investigations of colorless distributed combustion demonstrated significant improvement in pattern factor, low sound emission levels and ultra-low emissions of NO_x and CO [2–6]. CDC has been also investigated under different operational conditions [7] at high energy release intensities, with view to develop this technology for aviation applications [8]. The key requirement for distributed combustion involves uniform mixture preparation in the combustion chamber to avoid the presence of thin reaction zone and hot-spots in the flames via controlled mixing between the combustion air, hot reactive species and the fuel stream. High recirculation of hot reactive gases and its fast mixing with the oxidant and fuel leads to spontaneous ignition (auto-ignition) of the fuel with distributed reaction conditions. This feature avoids the formation of thin reaction zone and avoids the formation of hot-spot regions in the flame, which helps to mitigate thermal NO_x emissions produced from the Zeldovich thermal mechanism [1,9]. NO_x can also be formed via routes of prompt (Fenimore) NO_x and fuel NO_x, besides the thermal (Zeldovich) mechanism. Thermal NO_x can be mitigated by elimination of the hot spot zones in the combustor that arise from lack of mixture preparation prior to ignition. Also, thermal NO_x represents majority of the NO_x produced in gas turbine combustors.

The importance of incorporating reactive gases in air-fuel mixture preparation prior to ignition cannot be overstated. One common practice used to transport the reactive gases to stabilize combustion is via internal recirculation that has been used in swirl flows that actively entrains the reactive species from the combustion zone and transports them back to the root of the flame. For such combustors swirl characteristics play a dominant role in mixing, ignition and combustion [10–12]. In one of our previous investigations, the role of swirl air injection into the combustion chamber for distributed combustion reactions was explored [5]. Air was injected in a tangential swirling arrangement into the combustion chamber at high velocity. This air jet entrains large amounts of hot reactive gases forming an engulfment zone. The uniformly mixed fuel, air, and reactive gases at high temperatures then spontaneously ignite to result in a distributed combustion regime, instead of a thin concentrated flame front that occurs in traditional flames. The CDC cases discussed here are much different than that in conventional gas turbine combustors in that it does not require a flame holding device or low velocity region for flame stabilization. The hot reactive gases mix with the fresh mixture to help increase temperature of the mixture so as to cause spontaneous ignition (auto-ignition) in the entire combustion zone as compared to only a thin flame front exhibiting high temperature gradients which is a characteristic of conventional flames. Swirl combustors with tangential air entry have shown to exhibit ultra-low NO_x emission along with low CO emission under both premixed and non-premixed combustion mode, wherein NO emission below 2 PPM have been demonstrated [5,7] at high energy release intensity of 36 MW/m^3-atm at equivalence ratio of 0.7 using methane fuel.

The primary objective of this study is to evaluate fuel flexibility of the CDC combustor without changing any of its geometrical parameters. Different fuels are used in the combustor to assess the combustor fuel flexibility while maintaining ultra-low emission. The fuels examined include diluted methane, hydrogen enriched methane, propane, ethanol, and kerosene. Such wide range of fuels examined here, supporting fuel flexibility, are considered important in stationary gas turbines. A brief description of the examined fuels and their applications are given in the following section.

2. Examined fuels

2.1. Low calorific value fuel (diluted methane)

Numerous efforts have been reported on the use of various kinds of alternative fuels in existing power plants; however, for gas turbine applications the fuel quality and properties are of pinnacle importance. The combustion of low calorific gases, such as, landfill gas and producer gas can have some impact on the primary energy use while also reducing hazardous emissions. However, the composition and calorific value of these fuels can give problems with flame stability, combustion instability and high levels of pollutants emission. Low calorific value gases are produced from landfills and from some process industries so that their composition can be different not only between sites but also from operations. Upon removal of most of the trace organic compounds, landfill gas can be used as a source of clean fuel in gas turbines for power generation, heat and electricity. Producing energy from landfill gases has the additional benefits of onsite power generation for local use, and prevention of the gases release into the atmosphere and associated greenhouse effects. Municipal waste landfills emit mainly CO_2 and CH_4. The large amounts of CO_2 in landfill gas (typically 40–50%) presents problems with its utilization for energy production, since it adversely impacts flame stability, combustion efficiency and increased pollutants emission. Low calorific value associated with such fuels results in difficult operation of the combustor over a wide dynamic range of conditions with acceptable level of combustor performance. In contrast, the pyrolysis of organic wastes yields gases with high concentrations of H_2, CO, N_2 and CO_2. These mixtures can have very wide range of heating value and flame speed that depends on the fuel gas composition. The main combustion characteristics, such as, laminar flame speed and adiabatic flame temperature of landfill gas have been examined [13–15] with a view towards energy extraction. The economic aspects of energy production from landfill gases are discussed elsewhere [16,17]. Methane, diluted with nitrogen, is used here to simulate landfill gas as nitrogen and carbon dioxide have similar behavior in combustion environment [14,18].

2.2. Hydrogen enriched methane

Hydrogen enriched methane has shown considerable promise for ultra-lean premixed combustion for low emissions of NO_x, owing largely to the lower overall equivalence ratio which results in lower temperatures in the combustion zone. However, ultra-lean flames are susceptible to local flame extinction and local quenching, leading to undesirable flame characteristics, such as, flame quenching, poor combustion efficiency, combustion driven acoustic instabilities and mechanical failure of the equipment. Under