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Hydrogen addition effects on high intensity distributed combustion

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HIGHLIGHTS

- ▶ Examined distributed combustion for high intensity ultra low emission combustion.
- ▶ Novel design allowed stable combustion with hydrogen enriched methane.
- ▶ Stable high intensity combustion demonstrated at up to 36 MW/m^3-atm.
- ▶ Ultra low emissions (3 PPM NO and 9 PPM CO) and extended lean stability limits.
- ▶ Colorless distributed combustion for stationary gas turbines.

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ABSTRACT

Distributed combustion provides significant improvements under high intensity conditions characteristic of gas turbine to provide uniform thermal field (improved pattern factor), ultra-low pollution, enhanced stability and higher efficiency. Mixing between fresh air/fuel stream with hot reactive species is critical to result in distributed reactions and spontaneous ignition. Hydrogen enrichment of fuel is examined with emphasis on combustion stability and emissions under swirling flow conditions. Results are presented on the role of hydrogen enrichment to methane (4–15% by mass, 25–58.5% by volume) on the combustion characteristics under fuel-lean conditions. CO emission was substantially reduced with hydrogen enrichment, with minimal effect on NO emission under premixed combustion. Hydrogen addition extended the lean operational limits of the combustor with stable combustion and no flame fluctuations or flashback. Results obtained on pollutants emission and flame marking via OH* chemiluminescence revealed near volume distributed high intensity combustion with ultra-low emission (<3PPM NO and <9PPM CO) and high performance at lower equivalence ratio. Hybrid numerical–experimental approach can provide more realistic prediction of NO emission from hydrogen enriched methane combustion.

1. Introduction

The need for a combustor that surpasses the increasingly stringent regulation requirements concerning emissions from all kinds of propulsion and power systems along with quest for environment friendly energy systems have motivated combustion engineers to develop novel combustion techniques for achieving near zero emission of pollutants (such as, NO_x, CO, unburned hydrocarbons and soot) from gas turbine combustors. Also, the thermal field uniformity in gas turbine combustors is far from adequate as most current combustors can burn locally from non-uniform thermal field in the combustor to cause extensive downtimes of the system and increased emission of all pollutants. Colorless distributed combustion (CDC), which shares some of the principles of high temperature air combustion (HiTAC) [1], has demonstrated its ability to reduce emissions of NO and CO, and improve pattern factor through enhanced thermal field uniformity in the entire combustor. Reduced noise and stable combustion have also been shown under CDC conditions for gas turbine combustion condition. The flames in distributed combustion do not show any visible flame signatures so that the flame so formed is termed colorless due to negligible visible emission from the flames as compared to conventional flames. Under certain conditions green color flame is produced and we call this mode as 'Green Combustion Turbine'.

In HiTAC technology, high temperature of the air is obtained by preheating with the hot gases from within a furnace or reactor. The hot gases can be harvested from within the combustion zone or external to the combustion zone, using for example exit gases. The peak temperature in the flame zone is much reduced with the use of diluted low oxygen concentration combustion air even though the air is preheated to very high temperatures. This low oxygen concentration or diluted air is obtained from within the combustion chamber by entraining the highly reactive species into

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the incoming normal temperature combustion air or fuel. The effect of air preheats and reduced oxygen concentration on HiTAC flames have been studied, where it was found that pollutants emission, including CO and NO_x, and unburned hydrocarbons were much reduced with highly preheated combustion air at low O_2 concentration than that obtained with normal air [2].

Colorless distributed combustion (CDC) investigated here is focused on high combustion intensity for stationary gas turbine combustion application, although other applications are also possible. Previous investigations on volume distributed colorless combustion have shown significant improvement in pattern factor, low noise emission levels and ultra-low emissions of NO and CO [3–9]. To achieve reactions closer to distributed regime and avoid the presence of thin reaction zone and hot-spot zones in the flames (as seen in normal flames), controlled mixing between the reactants and hot reactive gases present in the combustion chamber is necessary to form hot and diluted oxidant with rapid evolution of distributed flame in the entire combustion chamber. High temperature reactive gases and its fast mixing with the reactants leads to spontaneous ignition of the fuel with distributed reaction in the entire combustion chamber. This combustion mode is significantly different than the normal combustion mode which results in a thin reaction zone and large temperature gradients. The distributed combustion regime not only avoids the formation of thin reaction zone, but also avoids the hot-spot regions in entire volume of the flame to mitigate the production of thermal NO_x emissions produced from the Zeldovich thermal mechanism [1,10].

The importance of entrainment of reactive gases into the fresh reactants with adequate mixing for ignition cannot be overstated. One common practice used to create recirculation and stabilize combustion is with swirl flow that entrains and recirculates a portion of the hot combustion species back to the root of the flame. For such combustors swirl characteristics play a major role in mixing and combustion [11–13].

In our previous investigations, the role of swirling air injection into the combustion chamber for seeking distributed combustion reactions was explored under different configurations [8,14]. Air was injected tangentially into the combustion chamber at high velocity to form swirling motion. This air jet entrains large amounts of reactive gases from within the combustion chamber. The amounts of entrainment are controlled so as to increase the temperature of the reactant mixture to a level higher than the auto-ignition temperature of the fuel. In non-premixed condition the fuel is injected at some distance downstream to provide sufficient mixing (desirable mixing time should be less than the ignition delay time). The uniformly mixed fuel/air/hot reactive gases then spontaneously ignite to result in a volume distributed reaction regime, instead of a thin concentrated reaction flame front. The CDC cases discussed here differ from conventional gas turbine flames in that no local flow reversal or low velocity region is required for flame stabilization. The reactive gas mixing with the fresh mixture help to increase temperature of the mixture high enough to cause spontaneous ignition in the entire combustion zone as compared to only small region of the fresh mixture as exhibited in conventional flames for flame stabilization. Swirl combustors with tangential air entry have shown to exhibit high swirl intensity, which helps reduce NO emission and enhance flame stability [15]. Also, ultra-low NO emission along with low CO emission have been demonstrated for swirling CDC combustor [8] under premixed combustion mode, with emission below 2 PPM of NO have been demonstrated at a high energy release intensity of 36 MW/m^3-atm at a rather high equivalence ratio of 0.7. Note that some authors also refer energy release intensity to heat release intensity in the literature. Different fuel introduction techniques have been examined for swirling CDC combustor with emphasis on low emissions [16].

Lean premixed combustion have been inherently used in gas turbine combustors to lower flame temperatures and to avoid stoichiometry non-uniformities that arise due to incomplete mixing of fuel and air. However, such method of lean premixed combustion often causes combustion instabilities, resulting in damage to the combustor and engine. Ultra-lean flames are susceptible to local flame extinction and quenching, leading to undesirable characteristics, such as, flame quenching, poor combustion efficiency, and acoustic combustion instabilities. In addition these flames produce elevated levels of carbon monoxide (CO) and unburned hydrocarbon (UHC) [17]. These premixed instabilities can lead to undesired phenomenon of flame flashback.

Higher combustibility of hydrogen has received increased attention as an additive to fuels for extending the lean combustion limits of gaseous fuels, reduce flame temperatures and reduce NO_x emissions. Ultra-lean combustion is possible by mixing hydrogen and gaseous hydrocarbon fuels for combustion in traditional gas turbines with low emission of NO_x, owing largely to lower overall equivalence ratio which results in lower flame temperatures in the combustion zone. Lower flame temperatures in the combustion-zone result in lower NO_x levels emanating from the Zeldovich thermal NO_x mechanism [10]. Note that the reduction of flame temperature results in weaker flames that are closer to the lean flammability limit.

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 quenching, leading to undesirable characteristics, such as, flame quenching, poor combustion efficiency, and acoustic combustion instabilities. Under distributed combustion conditions for gas turbine combustion, the addition of hydrogen to traditional hydrocarbon fuels show considerable potential of increasing lean flame stability and reduce NO_x emission. The enhanced lean flame stability allows stable ultra-lean combustion without any adverse effect on increased emissions of CO and UHC. Even though the addition of hydrogen may increase NO_x emission due to higher flame temperature, this can be offset by the ability to burn an overall leaner mixture so that lower thermal NO_x is produced [18–20]. Studies have been reported that describe the influence of hydrogen addition on flame stability and flame speed under fuel-lean condition in a swirl-stabilized flame [21]. The lean stability limit was extended significantly with the addition of hydrogen to hydrocarbon fuel in a combustor. The improved stability with hydrogen enrichment of the fuel was postulated to be from the direct result of higher OH, H and O radical concentrations in the resulting flames [22,23]. Higher NO_x levels have been reported in upstream region of the reaction zone with the addition of hydrogen, while nearly the same levels have been observed at further downstream positions in a premixed flame combustor for the same adiabatic equilibrium flame temperature condition [23].

Even though the role of hydrogen is well understood in theory, its practical application to combustors is still limited because hydrogen addition changes the fate of reaction zone significantly. In one of the studies, it was concluded that the effects of hydrogen addition on NO_x emissions vary according to the application [24]. Hydrogen addition to methane in shock tube lowered NO_x emissions, however, higher NO_x emissions were recorded for engine tests. Hydrogen addition to traditional hydrocarbon fuel in swirl-stabilized flames provides favorable effects, such as, lower emission of carbon monoxide and soot in a diffusion flame combustor. Then again, it sometimes has a negative effect on NO_x emission in premixed combustion system because the reaction zone is heated up by reduction in relatively cooler recirculation flow, especially with higher hydrogen addition and under lean burn condition