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Effect of hydrogen addition on combustion and emission characteristics of methane fuelled upward swirl can combustor

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ABSTRACT

The present research aims to assess the potential of hydrogen in the form of a supplementary fuel to accelerate combustion chemistry and reduce CO emissions of methane fuelled upward swirl gas turbine combustor. Effects of hydrogen enrichment on flame characteristics and chemical kinetics are analysed using Large Eddy Simulations (LES). Flame visualization is performed and measurements of temperature and emissions at the exit of combustor are reported. For the same energy input, flames are relatively broader and shorter at higher hydrogen concentrations. Augmentation of hydrogen is advantageous in terms of flame velocity, temperature, rate of chemical reactions and CO emissions. Higher flame temperature favours NO_x emissions at higher hydrogen content. At a constant volumetric fuel flow, reduction in carbon-generated species is attributed to hydrocarbon substitution and chemical kinetic effects are less. Hydrogen addition increases flame temperature, decreases flame dimensions and reduces CO emissions with marginal increase in NO_x emissions.

Introduction

Gas turbine engines fuelled by fossil fuels are widely used in aero industry and in stationary gas turbines for power generation. Land based systems are required to meet strict emission (NO_x, CO and CO_2) regulations. Lean and ultra-lean combustors are effective in reducing NO_x emissions but they suffer from issues related to flame extinction. Several methods are proposed to control the production of toxic pollutants from the combustor. Addition of steam/water to suppress thermal NO_x formation [1,2], achieve lean primary zone by premixed combustion [3], rich-burn/quick-mix/lean-burn (RQL) technique [4] and air/fuel staging [5] are few methods discussed in literature. Significant efforts have been made in the direction of replacement of conventional fuels by environment friendly alternative fuels. Substitution of fossil fuels by hydrogen fully [6–10] or partially [11–20] is a promising way to meet the stringent environmental norms. In the past few years, usage of hydrogen as an additional fuel in gas turbines has grown due to two reasons; one is increasing cost of fossil fuels and second is the adverse effect of exhaust gas emissions on climate. Hydrogen is a carbonless high energy density substance and has been widely used as a supplement with methane/natural gas to achieve efficient combustion, wider flammability limits and lower exhaust gas emissions from gas turbines [21]. Emadi et al. [22] conducted experimental study to observe the influence of hydrogen addition on

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Nomenclature

$\dot{m}_f$	Fuel mass flow rate
Q_i	Heat input
Ø	Equivalence ratio
Abbreviations	
LES	Large Eddy Simulations
CFD	Computational Fluid Dynamics
PDF	Probability Density Function
DO	Discrete Ordinates
LCV	Lower Calorific Value
GCV	Gross Calorific Value
SCADA	Supervisory Control and Data Acquisition

methane-air flame dynamics. It was reported that adding hydrogen to methane improves the flame stability limits. The burning rate was augmented with hydrogen enrichment to methane. Schefer [11] and Schefer et al. [12] reported that flame structure was significantly changed and lean flame stability limits were extended when hydrogen was supplemented with methane in a premixed burner. The leanest flame stability limits were observed with pure hydrogen in the burner. Hydrogen addition in methane had greatly reduced the CO formation without any adverse effect on NO_x emission formation. Burbano et al. [13] stated that addition of hydrogen in methane results into significant increase in OH radical concentration, which helps to promote the oxidation of CO into CO_2. Juste [14] presented that decrease in hydrocarbon weight and altered chemical kinetics due to hydrogen substitution could reduce CO emission by 40% for only 4% hydrogen fraction (by weight) in the fuel mixture. Emission measurements reported by Cozzi and Coghe [15] were different from others. In a non-premixed burner used by Cozzi and Coghe [15], higher soot formation was observed and CO and NO_x emissions were increased with increase in hydrogen content in fuel at a constant volumetric fuel flow rate condition. The increase of CO level was mainly attributed to reduction in residence time and increase in excess air with hydrogen addition. Higher NO_x emission level was mainly due to increased flame temperature with hydrogen addition. Flame structure analysis by Cozzi and Coghe [15] revealed that flames were relatively shorter and narrower at higher hydrogen concentrations, indicating intense mixing near the burner head and contributing to improved combustion of methane and flame stability. Zhao et al. [16] measured ignition temperature and burn off temperature to demonstrate effects of hydrogen enrichment on methane combustion. Measurements showed that both temperatures were decreased with hydrogen addition. CO emission was generated over a wide range of temperature when hydrogen was blended with methane.

Several computational studies have been reported investigating the combustion and emission characteristics of hydrogen-blended fuels in gas turbine combustors under different flow and operating conditions. Tabet et al. [23] numerically studied the effect of pressure on hydrogen-air flame structure under non-premixed regime. The investigations were carried out under constant volumetric fuel flow and airflow rates. Simulation results showed that mixing was deteriorated with increase in pressure. The OH radical, which is highly active intermediate radical in hydrogen-air flame, was found to decrease with increase in pressure. Shin and Liu [24] studied hydrogen addition effects on performance of a methane fuelled can combustor. Hydrogen was varied from 0% to 90% by volume in the mixture. Hydrogen addition at fixed fuel inlet velocity led to decrease in both fuel mass flow rate and total heat input, which resulted into drop in flame temperature and power shortage. When hydrogen was added for the same fuel flow rate, the heat input was increased with increase in hydrogen fraction. The flame temperature and exit gas temperature were increased due to release of larger heat in the combustor. CO emission was decreased with the addition of hydrogen while NO_x emission was increased due to increased flame temperature at higher hydrogen percentage. When the heat input was kept constant, the primary zone temperature was increased with hydrogen substitution but exit temperature was observed to decrease. This was attributed to wider and shorter flame produced at higher hydrogen fraction for same energy input. Emission of CO was increased at higher hydrogen percentage whereas NO_x emission was decreased at fixed heat input condition. Wang et al. [25] examined the hydrogen enrichment effects on methane-air combustion reactions. Results showed that the chemical reactions were promoted with hydrogen addition to methane due to increase of rate of formation of intermediate species like O, H and OH as hydrogen was added. The altered chemical kinetic due to hydrogen addition had little effect on NO production. With the help of numerical study, Bouras et al. [26] investigated flame properties of methane by adding hydrogen in a combustion chamber, which was used in gas turbine power plant. It was observed that increase of hydrogen fuel resulted into increase in velocity and temperature of burned gases. The enrichment of hydrogen reduced CO emission from the product gases at the exhaust.

In the previous work reported by Rajpara et al. [27,28], performance of upward swirl can-type combustor was studied using methane as fuel. It was analysed that the philosophy of upward swirl benefits in minimizing the NO_x emissions level from can-type gas turbine combustor. However, slower burning rate of fuel results into incomplete combustion, which produces significant amount of CO emissions from upward swirl combustor. Therefore, there is a need to accelerate the combustion chemistry in order to achieve higher burning rates of fuel and lower CO emissions of upward swirl combustor. The present research aims to assess the potential of hydrogen in the form of a supplementary fuel for the reduction of CO emissions from an upward swirl can-type combustor, which was originally designed and developed as a methane-fuelled combustor. Combustion and emission characteristics of hydrogen-containing methane fuels are studied under two different test conditions: hydrogen added at a constant heat input and hydrogen added at a constant volumetric fuel flow. Flame characteristics including axial velocity and temperature variations derived from LES are compared for pure methane and hydrogen blended methane