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Gas turbine combustion characteristics of H_2/CO synthetic gas for coal integrated gasification combined cycle applications

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ABSTRACT

This paper describes the gas turbine combustion characteristics of coal-derived synthetic gas (syngas), particularly for the syngases at the Taean IGCC plant in Korea and the Buggenum IGCC plant in the Netherlands. To evaluate the combustion performance of these syngases, we conducted combustion tests with elevated temperature and ambient pressure in a GE7EA model combustor. We observed flame stability, dynamic pressure characteristics, NO_x and CO emissions, temperature in the combustion chamber, and flame structures while varying the heat input and diluent integration ratio. Without dilution, Buggenum's stable regime is larger than that of Taean, since a higher hydrogen content causes sustained flames, even at a very high flame stretch rate. However, when considering nitrogen dilution, Taean's syngas has a more stable burn than that of Buggenum, since an increase in nitrogen at Buggenum has negatively affected flame stability. From the results of NO_x/CO emissions and combustion efficiency, we report that both syngases are sufficient to control NO_x emissions at under 5 ppm with almost complete and stable combustion; however, quantitatively, the effect of nitrogen dilution is slightly different at Taean and Buggenum due to slight differences in the H_2/CO ratio and diluent heat capacity. All the tested results and conclusions drawn are considered for optimal operation and trouble shooting at the Taean IGCC plant, which is scheduled to be complete toward the end of 2016.

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Abbreviations

C	Sonic velocity in the air at the temperature of T
$c_{p,i}$	Specific heat at constant pressure of i-gas
CCS	Carbon capture and storage
D_h	Hydraulic diameter
D_{swirl_in}	Inner diameter of swirler
D_{swirl_out}	Outer diameter of swirler
DR_{N2}	Dilution ratio of nitrogen
η_c	Combustion efficiency
IR_{N2}	Integration ratio of nitrogen
FL_{mix}	Flammable limit of mixture
FL_i	Flammability limits of binary sub-mixtures
IGCC	Integrated gasification combined cycle
LHV	Lower heating value
LFL	Lower flammable limit
$\dot{m}_i$	Mass flow rate of i-gas
$\dot{m}_{air}$	Mass flow rate of air
μ	Dynamic viscosity
P_3	Combustion chamber inlet pressure
$P'_{(3),\,rms}$	Root mean square of the dynamic pressure at the dump plane
PIV	Particle image velocimetry
ppm	Parts per million
ϕ	Equivalence ratio
R_{air}	Ideal gas constant for air
Re	Reynolds number
ρ	Density
S_n	Swirl number
SCGP	Shell coal gasification process
T_4	Combustor liner temperature
T_1	Air inlet temperature
T_{ad}	Adiabatic flame temperature
τ	Residence time
T_3	Combustion chamber inlet temperature
θ	Swirl vane angle
$\overline{U}_{jet}$	Jet velocity
UHC	Unburned hydro carbon
V_{pz}	Volume of the primary zone
x_i	Volume percentage of a sub-mixture in total fuel
[X]	Molar concentration of X species

Introduction

Background

IGCC is a potential technology for addressing the growing concern regarding global warming, urban atmospheric pollution, and depletion of energy resources. IGCC uses abundant low rank coal or renewable fuels such as biomass and agricultural or municipal waste, and offers environmentally clean benefits such as low NO_x combustion, syngas desulfurization, and CCS capabilities. Although this promising technology has been developed and demonstrated since 1990 at numerous sites (e.g., Wabashi River and Tampa in the US, Puertollano in Spain, Buggenum in the Netherlands and Nakoso in Japan), low plant availability in initial operation years is considered a serious issue. More precisely, unplanned outages due to fuel nozzle and liner burn out, combustion instability, and compressor surging in gas turbine units are the most critical sources of low availability [1–3]. Since we expect many outages in gas turbine combustors at new IGCC plants, due to the conditions at existing IGCC plants, a more detailed understanding of syngas combustion is necessary, and advanced syngas turbine technology should be adapted to improve IGCC production.

The first Korean IGCC project (power output: 300 MW_e; plant site: Taean) was launched in 2006 and is expected to be complete toward the end of 2015. For better operational availability and combustion optimization at this plant, we tested Taean syngas in a model GE7EA gas turbine combustor in this study to quantify potential application problems and evaluate its combustion performance as a gas turbine fuel.

Prior research on syngas turbine combustion

Due to the growing interest in IGCC during the last two decades, many researchers have studied syngas combustion. These syngas combustion studies are divisible into two categories: fundamental research on combustion characteristics—such as laminar burning velocity [4,5], ignition [6,7], flashback [8], blowout [9], flammable limit [10], and emissions [11–13]—and advanced research using gas turbine-like combustors under gas turbine-similar conditions [14–20].

As researchers in the first category, Natarajan et al. (2007) examined the effect of CO_2 dilution, preheating, and pressure on the laminar flame speed of H_2/CO mixtures by using two measurement approaches: flame area images of a conical Bunsen flame and velocity profile measurements of a one-dimensional stagnation flame [4]. Walton et al. provided an experimental data set on the ignition delay time of hydrogen and carbon monoxide syngases under high pressure and high temperature conditions [6]. From the regression analysis of their data set, they obtained the best-fit correlation between ignition delay time and experimental variables. Furthermore, Lieuwen et al. investigated the impact of syngas composition on four combustor-operability issues—blowout, flashback, combustion instability, and autoignition—by analyzing calculations obtained from the CHEMKIN program [9]. Giles et al. investigated the NO_x emission characteristics of syngas mixtures with airstream dilution of H_2O, CO_2, and N_2 in a counterflow diffusion flame. They found that the NO_x reduction effect of dilution was $H_2O > CO_2 > N_2$ [12]. Such scientific foundations have provided useful insights and information to use when analyzing results from advanced studies, which enables the development of rather economical approaches to understand combustion phenomena in syngas combustors before conducting complicated tests on full-scale engines.

Researchers in the second category have conducted studies, occasionally at great expense, to evaluate the combustion performance of syngas combustors and investigate syngas combustion characteristics in simulated gas turbine environments. Littlejohn et al. conducted combustion tests on a prototype injector of Taurus 70 engine for various syngas compositions and determined the lean blowout limits, log-linear dependency of NO_x, and the turbulent flame speed

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