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The effect of fuel composition on the characteristics of a non-premixed synthetic natural gas-air flame

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ABSTRACT

The variation of fuel composition in a non-premixed synthetic natural gas (SNG)-air flame was experimentally and numerically investigated in a lab-scale combustor with coaxial-type nozzles in order to determine the effect on flame stabilization and luminescence. Methane gas was blended with hydrogen and other hydrocarbon gases to modify the SNG, while compressed dry air was used as an oxidizer. The flow velocity at the nozzle exit was fixed at $u_F = 25$ m/s for fuel and $u_A = 0.17$ m/s for the oxidizer to measure flame behavior. Results showed that hydrogen addition to the fuel jet led to an increase in flame stabilization and a decrease in liftoff height. The maximum intensity of light emission was at a wavelength 308 nm. The adiabatic flame temperature increased with hydrogen addition to the fuel jet. The mole fraction of H_2O increased, while the mole fraction of CO_2, CO, NO, and OH decreased with the addition of C_3H_8 and H_2 to the fuel jet.

1. Introduction

Concerns about increasing pollutant emissions and natural resource depletion have led to studies of synthetic gas (syngas) combustion as a clean coal combustion [1,2]. The most popular method to produce syngas is coal gasification or reforming low-rank coal. Coal gasification is known to be a carbon capture technology that is responsible for global warming and climate change. Integrated gasification combined cycle power plants are considered to be a substitute for traditional coal-fired power plants to improve thermal efficiency and achieve zero pollutant emission [2].

The use of syngas provides a practical use of low-rank coal, which was regarded as an economically useless resource for traditional coal-fired power plants in the past. In recent years, efforts have been made to use syngas as a form of synthetic natural gas (SNG), which is blended with natural gas. Hydrogen in syngas causes hydrogen brittleness in old city gas pipes, and SNG is a practical method because it can use syngas without retrofitting the existing pipeline network. Nevertheless, the characteristics of SNG flames are thought to differ from conventional natural gas because SNG is composed of hydrogen (H_2), methane (CH_4), and other hydrocarbon gases [3,4].

Walton et al. numerically and experimentally studied ignition delay times of oxy-syngas flames for application in a gas turbine combustor [5]. The volumetric ratio of hydrogen and carbon monoxide (H_2/CO) gases varied from 0.25 to 4.0. They derived the experimental formula as a function of pressure (7.1–26.4 bar), temperature (855–1051 K), equivalence ratio (0.1–1.0), and oxygen mole fraction (15–20%). The ignition delay time increased with increasing temperature and decreased with the increase of pressure, equivalence ratio, and oxygen mole fraction.

Wu et al. numerically and experimentally investigated the laminar flame speed of various hydrocarbon-fueled mixtures (ethane, ethylene, acetylene, and CO) [6]. They reported that the flame speed increased with H_2 addition in reactive mixtures. For CO combustion, CO oxidation was accelerated by even small amounts of H_2 addition due to the strong catalytic influence of H_2 on the CO oxidation process.

Vu et al. numerically and experimentally studied cell formation and burning velocity of a laminar premixed syngas-air flame in a constant pressure combustion chamber with increasing surrounding pressure (P_∞) from $P_\infty = 1$ to 4 bar [7]. They found that cellular instability increased with increasing H_2 addition and preferential instability did not decrease with methane addition due to the decrease in the effective Lewis number.

Fu et al. experimentally studied the burning velocity of a laminar premixed syngas-air flame in a Bunsen burner [8]. They found that burning velocity and flame temperature increased while chemiluminescence intensity decreased with increasing hydrogen mole fraction in reactants (X_{H2} = 20-80%). From kinetic analysis, the hydrogen molecules carried out an important role in accelerating the chemical reaction.

In the current study, the variation of fuel composition in a non-premixed synthetic natural gas (SNG)-air flame was experimentally investigated in a lab-scale combustor with coaxial-type nozzles. Methane gas was blended with hydrogen and other hydrocarbon gases to

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Nomenclature

A	pre-exponential factor (kgmol/m^3/s)
a.u.	arbitrary unit
b	temperature exponent
CH*	chemiluminescence from methylidyne radicals (CH)
DO	discrete ordinates
DSLR	digital single lens reflex
d_A	outlet diameter at a coaxial air nozzle exit (mm)
d_F	outlet diameter at a fuel jet nozzle exit (mm)
ED	eddy-dissipation
EDC	eddy-dissipation concept
EVM	eddy viscous model
E_a	activation energy (J/kg/mol)
Fr_i	Froude number of species i ($=u_i^2/(d_F \times g)$)
FL	focal length of a lens or spectrometer (mm)
f#	f-number of a camera or lens
g	acceleration of gravity (m/s^2)
H	liftoff height (mm)
ISO	international organization for standardization
I_λ	intensity of light emission (a.u.)
k_G	global reaction rate ($=AT_\infty^b\exp(-E_a/RT_\infty)[X_A]^m[X_B]^n$)
MFC	mass flow controller
MFM	mass flow meter
m, n	reaction order
OH*	chemiluminescence from hydroxide radicals (OH)
P_∞	atmospheric pressure (bar)
RANS	Reynolds averaged Navier–Stokes
Re_i	Reynolds number of species i ($=u_i \times d_F/\nu_i$)
RKE	realizable k-ε model
r	radial distance (mm)
SIMPLE	semi-implicit method for pressure linked equations
SNG	synthetic natural gas
T_{Ad}	adiabatic flame temperature (K)
T_A	coaxial air temperature (°C)
T_{co}	coflow air temperature (°C)
T_F	fuel jet temperature (°C)
T_∞	surrounding temperature (°C)
t_{exp}	exposure time of a camera (s)
$t_{F,lip}$	lip thickness of a fuel jet nozzle (mm)
$t_{A,lip}$	lip thickness of a coaxial air nozzle (mm)
u_A	coaxial air velocity at a nozzle exit (m/s)
u_{co}	coflow air velocity at a nozzle exit (m/s)
u_F	fuel jet velocity at a nozzle exit (m/s)
X_i	volumetric mole fraction of species i (%)
x	axial distance (mm)
ρ_i	density of species i (kg/m^3)
λ	wavelength of light emission (nm)
ϕ_G	global equivalence ratio
ν_i	kinematic viscosity of species i (m^2/s)
ω_i	reaction rate of specie i (kg/m^3/s)

modify SNG, while compressed dry air was used as an oxidizer. Flame stabilization, flame luminescence, and temperature inside the lab-scale furnace were measured to study the effect of varying fuel compositions on flame characteristics.

2. Experimental methods

The experimental setup for the measurement of flame appearance, flame spectra, and time-averaged temperature comprised a lab-scale combustor, digital single lens reflex (DSLR) camera, spectrometer, and data acquisition (DAQ) system.

2.1. Lab-scale combustor

The internal dimensions of the lab-scale combustor were width 100 mm, depth 100 mm, and height 400 mm. Each wall was equipped with a quartz window to allow optical measurement. Coaxial-type nozzles were used for fuel in the center and for coaxial and coflow air. The diameter and lip thickness of the nozzle exit was $d_F = 2$ mm and $t_{F,lip} = 1$ mm, respectively, for the fuel jet and $d_A = 20$ mm and $t_{A,lip} = 12$ mm, respectively, for the coaxial air. Coflow air was injected around the coaxial air nozzle to fix global equivalence ratio (ϕ_G). Fig. 1 shows a schematic of the lab-scale combustor and a cross section of the fuel and coaxial air nozzles.

2.2. Flow rate regulation

The flow rate of the fuel jet and coaxial and coflow air was regulated with a mass flow meter (MFM) and mass flow controller (MFC) (5851E, Brooks Instrument Co., Hatfield, PA, USA). The MFM and MFC were controlled by Lab-VIEW modules (NI cDAQ 9172, NI 9263, and NI 9205; National Instruments Co., Austin, TX, USA) and the flow control system of the MFM, MFC, and Lab-VIEW modules was calibrated by a dry gas test meter (DA-16A-T; Sinagawa Co., Tokyo, Japan).

2.3. Visible flame measurement

A DSLR camera (D300s, Nikon Co., Tokyo, Japan) was used to take visible flame images and was mounted with a macro zoom lens (AF-S Nikkor, 24–70 mm, f/2.8; Nikon Co., Tokyo, Japan). The photographic conditions were f-number (f#) = 8, exposure time (t_{exp}) = 1/200 s, and light sensitivity ISO 1000.

2.4. Flame spectra measurement

A spectrometer (Acton SP2150i for grating body, spectra hub for signal controller, and PD471 for photo-diode; Princeton Instruments Inc., Trenton, NJ, USA) was used to analyze the spectral characteristics of a non-premixed SNG-air flame. The focal length of the spectrometer (FL) was 500 mm. Measuring wavelength (λ) was from 100 to 1000 nm. The flame spectra were measured five times at each condition at a resolution of 1 nm.

2.5. Experimental conditions

Flow velocity at the nozzle exit was varied as u_F = 5-40 m/s for the fuel jet and u_A = 0-0.43 m/s for the oxidizer to measure flame stabilization, while flow velocity at the nozzle exit was fixed at u_F = 25 m/s and u_A = 0.17 m/s to measure flame appearance, flame spectra, and time-averaged temperature. The fuel composition of the SNG is summarized in Table 1. Experiments were carried out at normal temperature T_∞ = 300 K and atmospheric pressure P_∞ = 1 bar. The Reynolds number of species i (Re_i) was defined as $Re_i = u_i \times d_i/\nu_i$, where ν_i is the kinematic viscosity of species i. The Froude number of species i (Fr_i) was defined as $Fr_i = u_i^2/(d_i \times g)$, where g is the acceleration due to gravity. The test conditions are summarized in Tables 2 and 3.

3. Numerical methods

Numerical method were used to calculate the adiabatic flame temperature and mole fraction of products with a GasEq program [9] and the distribution of velocity, temperature, and species with a Fluent program [10] in a CH_4-air flame. Numerical results are helpful for compensating for the limitation of the experimental measurement if it is exactly predicted.