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Combustion characteristic and heating performance of stoichiometric biogas–hydrogen–air flame

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ABSTRACT

An experimental study has been conducted to investigate stoichiometric biogas–hydrogen mixed fuel flames and the combustion characteristic and heating performance of three biogases enriched with hydrogen were examined. Both similar flame behavior and new finding are reported with reference to the literature.

The dependence of flame stability on the fraction of hydrogen and the CO_2 concentration was analyzed in the aspects of fuel property alteration and flow aerodynamics variation. The experiments showed a favorable effect of hydrogen and detrimental effect of CO_2 on flame stability. Examination of flame cone height showed that under constant Re and Φ, the cone height is longer at either higher hydrogen fraction or higher CO_2 concentration. In addition, at higher fraction of hydrogen in the mixed fuel, flame flammability strengthens, flame temperature enhances and CO emission reduces. Further, polyhedral reaction cone was detected for stoichiometric flames under high hydrogen concentration conditions.

Great care was paid to the heat transfer behavior of stoichiometric biogas–hydrogen flames. First, when the cone tip touches the copper plate, the stagnation point heat flux is not the maximum peak when compared to heat flux peaks at other nozzle-to-plate distance. Comparison between two flames of identical cone height indicated that higher flame temperature is a dominant factor influencing heat transfer. Further, longer flame height tends favor heat transfer only at large nozzle-to-plate distances.

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1. Introduction

Biogas is a future alternative to traditional fossil fuels. As it is derived from landfills, agricultural wastes and other sources of biomass, biogas is environmentally-friendly and renewable. With increasing interest in utilization of biogas, especially in rural areas [1], better exploration of biogas is under investigation of many researchers.

The constituents of biogas are mainly methane and carbon dioxide, with smaller amounts of hydrogen sulfide, moisture and siloxanes. The molar fraction of carbon dioxide (CO_2) is high, which ranges from 40% to 60% depending on the source of biogas, so biogas is a low-calorific-value fuel. Due to the high content of diluting gas CO_2, the combustion characteristics of biogas are inferior to natural gas.

Many attempts were made to upgrade the combustion characteristics of biogas [2–5]. Lee and Hwang [3,4] proposed the method of adding a higher-grade fuel to biogas to raise its heating value. The authors devoted to biogas–liquefied petroleum gas (LPG) mixed fuel, and observed higher heating value as well as higher burning velocity of the mixed fuel in comparison with raw biogas. They found that the biogas–LPG mixed fuel can be used interchangeably with liquefied natural gas. Cardona and Amell [5] added both propane and hydrogen to biogas, and observed that laminar burning velocity of the fuel mixture is higher than pure biogas due to introduced propane and hydrogen.

Interest in upgrading biogas by addition of hydrogen to improve the fuel quality has grown in recent years. Research efforts were firstly devoted to flame stabilization by using hydrogen addition. Leung and Wierzba [6] experimentally tested the stability of a biogas–hydrogen diffusion flame, and observed a substantially wider stable operational range even though the fraction of hydrogen in the biogas–hydrogen mixture is low. Zhen et al. [7,8] observed improved stability for both diffusion and premixed flames caused by hydrogen addition to biogas.

Meanwhile, research attention was paid to the variations in flame temperature and pollutant emission that caused by addition of hydrogen to biogas. Most researchers reported higher flame temperature, higher reaction rate and lower carbon monoxide

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Nomenclature

Re	Reynolds number of fuel/air mixture jet
ρ_{mix}	density of fuel/air mixture, kg/m^3
V_{exit}	flow velocity at burner exit, m/s
d	inner diameter of the nozzle, m
Φ	mixture equivalence ratio
V_{fuel}	volume flow rate of fuel, m^3/s
V_{air}	volume flow rate of air, m^3/s
α	molar fraction of hydrogen in the fuel mixture, %
μ_{mix}	dynamic viscosity of fuel/air mixture, N · s/m^2
μ_{i}	dynamic viscosity of component *i*, N · s/m^2
Y_{i}	mole fraction of component *i*, %
M_{i}	molecular weight of component *i*, kg/mol
EICO	emission index of CO, g/kg

(CO) emission for biogas–hydrogen mixtures in comparison to raw biogas [5,7,8]. Furthermore, some researchers [7,8] investigated the heating performance of biogas–hydrogen flames. Zhen et al. [7] examined a biogas–hydrogen diffusion flame and pointed out that its low sooting characteristic is favorable for domestic heating applications. The heat transfer rate from the diffusion flame to the target plate decreased when more hydrogen was added to the biogas. While in the study of a biogas–hydrogen premixed flame, the total heat transfer rate was found to be enhanced at higher fraction of hydrogen addition [8].

The literature on the combustion characteristics of biogas–hydrogen flames [5–8] is relatively scarce in comparison to the numerous studies conducted on methane–hydrogen flames. To name a few, the methane–hydrogen fuel was found easier to ignite and accelerate the relative slow reaction rate of the menthe fuel [9–11], thereby improving flame stability and reducing pollutant emissions [12–14]. Compared to the methane–hydrogen fuel, the biogas–hydrogen fuel has a presence of CO_2 which deteriorates the thermal and emission performance of the flame [15].

The afore-review indicates that only a few studies were previously conducted on the thermal and emission characteristics of biogas–hydrogen flames, with less attention put on the heating performance. As biogas is in wide use for cooking purpose in rural areas, the heat transfer behavior of the impinging flame is also an important parameter to be investigated. In the current work, three biogas/air flames with different levels of hydrogen addition will be experimentally investigated, with both the combustion characteristics of open flames and the heating performance of impinging flames to be tested. It is expected that the findings drawn from this study will provide direct guidance for better utilization of biogas for practical applications.

2. Experimental setup and method

Fig. 1 schematically shows the experimental setup for this study. It mainly includes thermocouples, gas emission analyzers and a test rig for measuring heat flux from impinging flames to a target copper plate. In this study, biogas was prepared by mixing pure gases of CO_2 and methane (CH_4). The volumetric ratios of CO_2 and CH_4 were changed from 4:6 to 5:5 and 6:4, and these three biogases were referred to as BG_{60}, BG_{50} and BG_{40}, respectively. For each biogas, pure hydrogen was introduced in and the volumetric ratio of hydrogen to the biogas is:

$$\alpha = \frac{V(H_2)}{V(CH_4) + V(CO_2)} \times 100\% \tag{1}$$

All three gases were of over 99% purity to minimize variation in the composition of the mixtures prepared. Compressed air is used as the oxidizer. Prior to the burner, both fuel and air flow rates were monitored by appropriate flow meters, and then were mixed together by a cylindrical mixing chamber. The burner used is a copper tube, having 9 mm inner diameter and 11 mm outer diameter. The tube is 400 mm long such that fully developed flow can be established at the burner exit. For each flame established, the Reynolds number (Re) was adopted to represent the aerodynamic characteristics of the jet flow:

$$Re = \frac{\rho_{\text{mix}} V_{\text{exit}} d}{\mu_{\text{mix}}} \tag{2}$$

where dynamic viscosity of gas mixture, μ_{mix}, was calculated according to Ikoku [16]:

$$\mu_{\text{mix}} = \frac{\sum\left(\mu_{\text{i}} Y_{\text{i}} \sqrt{M_{\text{i}}}\right)}{\sum\left(Y_{\text{i}} \sqrt{M_{\text{i}}}\right)} \tag{3}$$

The equivalence ratio (Φ) of the fuel/air mixture is:

$$\Phi = \frac{\text{fuel-to-air-ratio}}{(\text{fuel-to-air-ratio})_{st}} = \frac{V_{\text{fuel}}/V_{\text{air}}}{(V_{\text{fuel}}/V_{\text{air}})_{st}} \tag{4}$$

where the suffix *st* stands for stoichiometry. The current study focuses on stoichiometric flames to bring out distinct flame behavior at $\Phi = 1.0$, in contrast to the previous study of a biogas–hydrogen flame at $\Phi = 1.2$ [8].

Experiments were conducted to test the flame stability. For each biogas, i.e. BG_{60}, BG_{50} and BG_{40}, ignition was made near the burner exit to check whether the flame can be stably operating or not. The operational conditions tested are $Re = 400$, 600 and 800, and $\Phi = 1.0$. Then, hydrogen was added to the biogas and such ignition testing was repeated for biogas–hydrogen flames. For the latter flames, the fraction of hydrogen added in the biogas–hydrogen mixtures increased from 10% to 50%, at an interval of 10%.

To capture luminous photos of the biogas–hydrogen flames, a high-resolution CCD camera with a shutter speed of 1/60 s was used. The flame height, defined as the vertical distance from the burner exit to the flame tip, was measured by using a ruler of 0.5 mm precision. Flame temperature was measured by an uncoated B-type thermocouple which has a wire diameter of 0.25 mm. The registered temperatures were then corrected for radiation and conduction loss.

Carbon monoxide emitted by the flames was examined and emission index, which is expressed in grams of CO emitted per kilogram of fuel (biogas plus hydrogen) burned, was used to represent the overall carbon monoxide emission. A tapered quartz probe was placed 70 mm above the flame tip to collect flue gases. Next, the sampled gases were condensed to remove water vapor. Then, the volumetric CO/CO_2 concentrations in the sampled gases were measured by a CO/CO_2 analyzer (California Instruments Corp., Model 300, NDIR).

The test rig for measuring impinging heat flux consists of a copper plate which acts as a target surface, and a heat flux sensor which was inserted to the copper plate, with the sensing face flush with the plate surface on the flame side. It is a small ceramic heat flux sensor (Vatell Corporation, Model HFM-6D/H) with an effective sensing area of 2×2 mm^2, being able to simultaneously measure conduction, convection and radiation heat transfer from the flame to the plate. The sensor is supplied with a NIST traceable

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