Effect of Hydrogen Addition on Biogas Combustion and Flame Propagation

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ABSTRACT

Combustion and burning velocity of hydrogen enriched biogas-air mixture have been investigated in this study from an equivalence ratio of 0.4 up to stoichiometric. Hydrogen addition was varied from 10 to 40% based on the volume fraction. Flame buoyancy was observed for leaner mixture especially at an equivalence ratio of 0.4, while mild cellularity was observed for the equivalence ratios of 0.4 and 0.5 during the later stage of the flame propagation. Flame appears to become less stable under leaner conditions as supported by the occurrence of buoyancy and mild cellularity at the equivalence ratios of 0.4 and 0.5 under 30% and 40% of hydrogen addition. It was found that for 30% and 40% addition, the flammability limits extend to the leaner side. The maximum burning velocity occurs at an equivalence ratio of 0.8 for all mixtures regardless of the hydrogen enrichment percentage. The flame speed was enhanced with hydrogen enrichment at higher than 30% which led to a significant increase in the burning velocity These observations show that the addition of hydrogen into biogas combustion will lead to an increase in the flame propagation and burning velocity.

Keywords: *Biogas, hydrogen addition, burning velocity, cellularity*

1.0 INTRODUCTION

Biogas generally is composed of methane, CH_4 with a composition of 60 to70% and carbon dioxide, CO_2 with composition of 30 to 40% with several traces of other gases such as nitrogen, N_2 and hydrogen sulfide, H_2S at relatively small and negligible percentage [1]. Due to its abundance and renewability, biogas could be a promising alternative fuel for the future. There are however several inherent drawbacks with regards to using the biogas to power the combustors, particularly at smaller heating value and altered flame behavior due to the presence of CO_2; higher CO_2 percentage may further reduce the heating value and exacerbate the flame behavior especially in terms of flammability, propagation speed and stability.

The addition of hydrogen, H_2 as an additive to improve the combustion of several gaseous fuels has been reported in literature. This is due to its wider flammability range and zero CO_2 and CO emission. However, H_2 burns with a characteristically unstable flame due to its smaller molecular weight and lower density [2].

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These characteristics could make H_2 as a complementary additive to biogas that has a narrower flammability range and relatively higher molecular weight and density. It is interesting to postulate if H_2 addition within certain range could result in favorable combustion.

Zhen *et al*. measured the laminar burning rate of biogas-H_2-air mixture using *Bunsen* burner with H_2 volume varied from 10 - 50% [3]. They found out that there was a corresponding increase in the biogas burning rate with H_2 percentage increase. The peak of burning rate also shifted from stoichiometric to the richer side at an equivalence ratio of 1.2. Flame stability has also improved with H_2 addition with lower propensity towards blow off and flash-back. The effects of the stretch, however was not addressed along with the flame thickness and density gradient across the flame zone on flame stability. Mameri and Tabet conducted a numerical study on biogas-H_2-air mixture counter-flow diffusion flame [4]. Flame has been found to be less affected by the strain rate and emits less radiation at H_2 percentage of 20%. However, at this particular conditions, H_2 addition does not significantly counteract the chemical effect of the CO_2 on biogas combustion and no data on burning rate were reported since it involves the diffusion flame.

Zhen *et al*. studied biogas-H_2-air mixture with H_2 addition up to 50% [5]. They found that H_2 addition could counter the negative effects of CO_2 as evidenced by an increase in the burning rate, flammability and flame stability. However, they limited their study to stoichiometric mixture and even though *Bunsen* flames are generally prone to curvature and stretching, the influence of the stretch was not included. Wei *et al*. also performed biogas-H_2-air combustion study using *Bunsen* burner and observed an increase in the total heat transfer rate by almost 30% at 30% H_2 enrichment [6]. They attributed the enhancement in the total heat transfer rate to an increased flame temperature and H_2 higher diffusivity. However, data on the burning rate and the effect of flame stretch were not included in their study.

This study attempts to investigate the burning rates and flame stability by considering the effects of the hydrodynamic instabilities using a spherically expanding flame method under the initial conditions of 1 bar and a temperature range of 25°C to 29°C. *Schlieren* images of the spherically expanding flames were analyzed to obtain the flame speed from which the aforementioned parameters could be determined.

2.0 EXPERIMENTAL SETUP

Experiments were conducted in a constant volume combustion chamber with an initial pressure of 1 bar and temperature range of 25°C to 29°C. Figure 1 shows the overall system employed in this study consisting of an ignition system, linear *Schlieren* optical setup coupled with a combustion chamber and data acquisition system. The combustion chamber is in cylindrical form having a volume of 29 L with two optical windows at each side for optical access. A pair of electrodes are placed at the centerline of the chamber to provide the central ignition. The linear *Schlieren* setup comprised a pair of collimating and focusing lens with a diameter of 150 mm, an LED light source and a *Phantom 7.1* high-speed camera. After the combustion chamber was vacuumed, it was filled with biogas followed by H_2 and air with partial pressures that correspond to the designated equivalence ratios, ϕ, ranging from 0.4 to 1.0. The biogas content was initially characterized using gas chromatography and tabulated as shown in Table 1. Gaseous traces that were detected in the biogas are mostly composed of N_2 and to a lesser extent of H_2S [1]. The images of the spherically expanding flames were recorded by *Phantom 7.1* high-speed camera connected to a notebook PC after the mixtures of biogas-H_2-air were ignited. The captured images were then analyzed using an image processing software; *Adobe Photoshop* and *MATLAB* to obtain the equivalent flame radius. The differentiation of the flame radius with respect to time yields the flame speed from which the laminar burning rate, u_L and flame stretch, α could be derived.

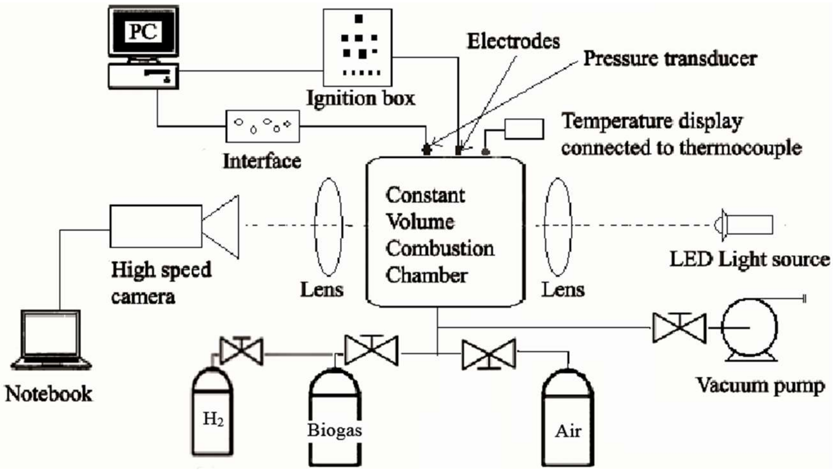

Figure 1: Experimental setup

Table 1: Composition of the actual biogas in the present study

Biogas	**Composition**		
Gas	CH_4	CO_2	Others
Percentage (%)	49-52	48-51	0.3-1.1

For a spherical flame, u_L represents the rate at which the fuel and oxidizer consumption can be derived from the time rate change of the flame radius, where the stretched flame speed, S_n and flame stretch, α are given by [1]:

$$S_n = \frac{dr}{dt} \tag{1}$$

$$\alpha = \left(\frac{2}{r}\right)\frac{dr}{dt} \tag{2}$$

$$\alpha = \left(\frac{2}{r}\right)S_n \tag{3}$$

By including the effect of stretch on the flame propagation rate yields:

$$S_s - S_n = L_b\alpha \tag{4}$$

where S_s is the unstretched flame speed and L_b is essentially the slope of the plot of S_n against α. The unstretched flame speed also enables the determination of the burning rate, u_L, by the relation:

$$u_L = S_s\frac{\rho_b}{\rho_u} \tag{5}$$

The term $\left(\frac{\rho_b}{\rho_u}\right)$ represents the density ratio of the burned and unburned gas and calculated under the assumption of the adiabatic constant pressure combustion. The definition of the H_2 addition, β is adopted from [5] and is defined by:

$$\beta = \frac{V_{H_2}}{V_{CH_4}+V_{CO_2}} \tag{6}$$

where V is the volume fraction for each gas.

3.0 RESULTS AND DISCUSSION

Figure 2 shows the *Schlieren* photographs of the spherical flame propagation of actual biogas and biogas with hydrogen addition at 10% and 40% at an equivalence ratio of 0.8. At this particular condition, the flame front appears to be smooth for all flames. The flame radii for hydrogen enriched flame however tend to increase at a much faster rate compared to the pure biogas. The rate tends to increase appreciably with an increase in the hydrogen addition. This suggests the effect of H_2 addition which tends to accelerate the fuel propagation due to improved mass and thermal diffusion.

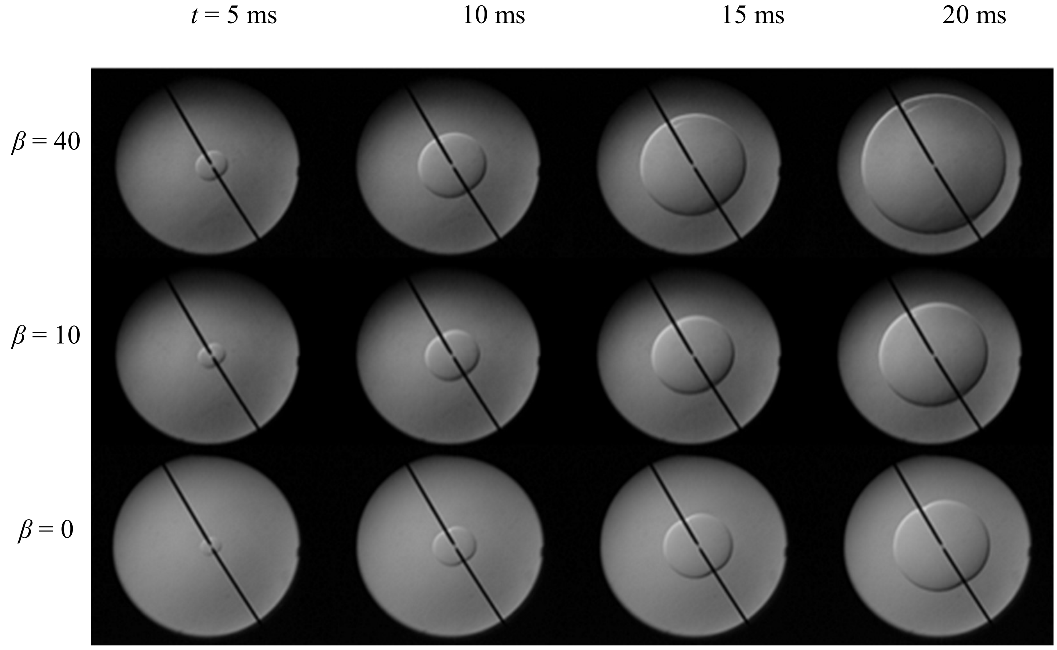

Figure 2: Spherical flame development (with 5 ms interval) for pure biogas and hydrogen enriched biogas at 10% and 40% addition at an equivalence ratio of 0.8

Figure 3 depicts the *Schlieren* photographs of the hydrogen enriched biogas at 30% and 40% addition at equivalence ratios of 0.4 and 0.5. As can be seen from these images, at the equivalence ratio of 0.4, both flames with 30% and 40% addition experience a buoyancy while the flame of 0.5 shows less buoyancy but with a cellularity at t = 50 ms. This shows that the hydrogen addition at this particular percentage could improve the flammability to the leaner side but the resulting flames are susceptible to instabilities. The less symmetrical shape suggests instability that is driven by preferential diffusion [7]. Miao *et al.* also observed the same kind of instability at the leaner side for the LPG-H_2-air mixture [2]. Even though the buoyancy is apparent for a flame of 0.4, its sufficient thickness prevents the formation of the cellular structure at the lower portion (downwardly propagating) of the flame [8]. Otherwise, if the flame is sufficiently thin, cellularity will emerge. Buoyancy has also been shown to possess the stabilizing effect on the large wavelength disturbances for downwardly propagating flame [8]. The fact that there are no cells formation, a flame of 0.4 might suffer from large wavelength disturbances which is stabilized by buoyancy. Thus, there are two factors that come into play in suppressing the formation of cells, in this case, the flame thickness and buoyancy. Figure 3 also shows the cells formation at some portions of the flame of 0.5 in the vicinity of the electrodes. Cells formation at this particular equivalence ratio could be influenced by the combination of a number of factors. Flow perturbation due to the electrodes combined with a sufficiently low flame thickness may contribute to cell formation.

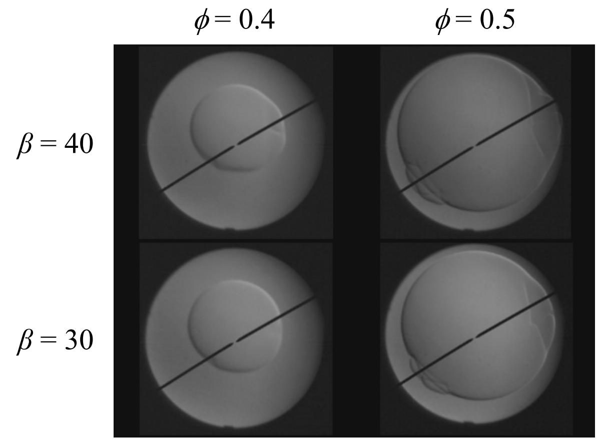

Figure 3: Spherical flames of hydrogen enriched biogas at 30% and 40% addition at equivalence ratios of 0.4 and 0.5.

Figure 4 shows the comparison of the flame speed variation with time of the biogas and hydrogen enriched biogas with 10 to 40% addition at an equivalence ratio of 0.8. The plot shows a characteristic flame speed progresses with time and a noticeable decrease from the point of ignition to a certain minimum point before a rise in the flame speed occurs. This observation is caused by the radicals from the spark that quickly dissipates to the minimum point [9]. The spark also creates a shockwave that propagates outward, followed by a slower thermal wave. The thermal wave front usually has high initial speed that rapidly decreases over a short period of time [10]. After the minimum point, flame speed starts to increase again until it stabilizes as the combustion progresses. This stabilized region is dominated by the normal chemistry as the spark radicals diminishes.

There are also noticeable differences in the manner in which the stable flame speed was established at different hydrogen additions. Flame speed shows a sharp decrease during the first few milliseconds with the flame of 30% and 40% enriched mixture shows a much more prominent decrease. The flame of 30% and 40% H_2 addition also shows a faster flame propagation and acceleration after it has reached a minimum value of the flame speed. A similar trend was observed for 10% and 20% H_2 addition but with smaller magnitude of the increment. Generally, it clearly indicates that the addition of hydrogen resulted in an increase in the rate of flame propagation as well as acceleration.

Figure 5 shows the comparison of burning velocity for different equivalence ratios and hydrogen addition from a single experiment. For each condition, the experiment was repeated up to three times for ensuring the repeatability of experiment. In general, the hydrogen addition could increase the flammability limit of biogas-hydrogen enriched particularly on the leaner side if the addition is beyond 30%. There is a significant increase in the burning velocity as hydrogen addition was increased from 10% to 40%. The difference is quite small for 10% and 20% addition. However, for 30% and 40% addition, burning velocity started to increase significantly where the value exceeds the burning velocity of pure methane. This enhancement was approximated of about two times higher than the burning velocity of actual biogas. The significant increase in burning velocity can be related to the increase in the production and diffusion of active radicals in the reaction zone [3].

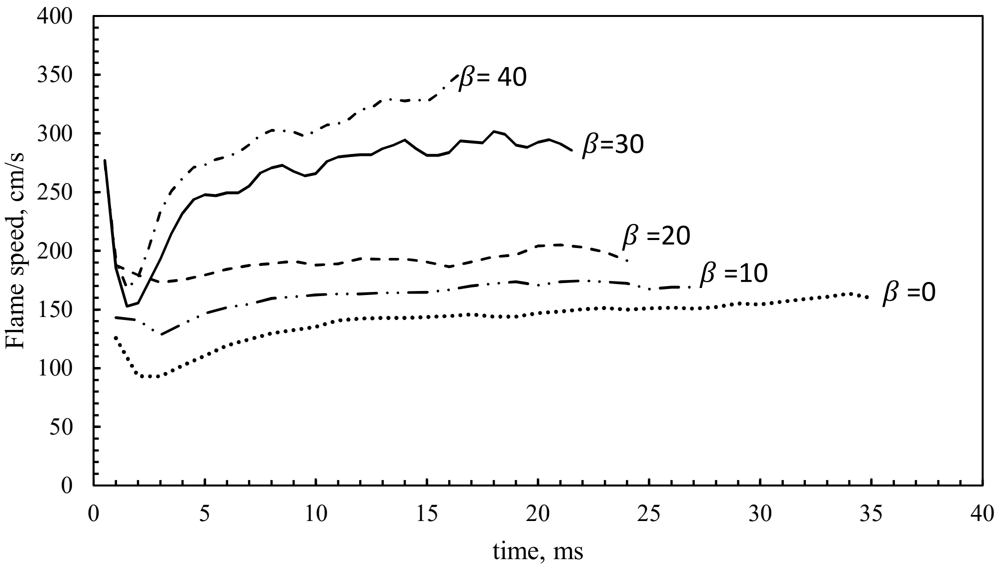

Figure 4: Comparison of the flame speed variation with time of the actual and hydrogen enriched biogas with 10 to 40% addition at an equivalence ratio of 0.8.

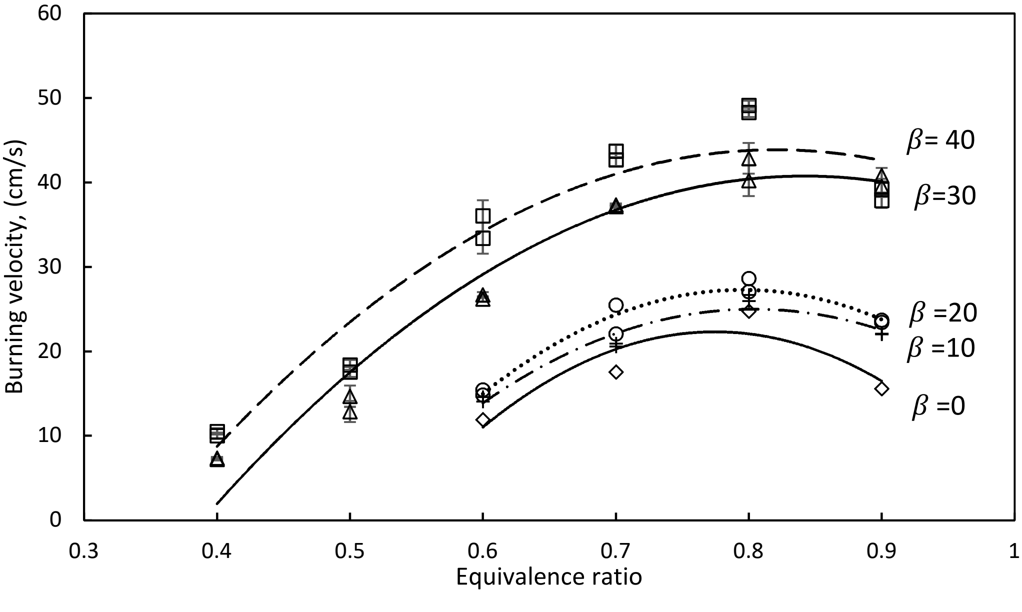

Figure 5: Comparison of the burning velocity at different hydrogen addition and equivalence ratios

4.0 CONCLUSION

Experiments on biogas spherical flame propagation and burning velocity have been performed with various H_2 addition under an initial condition of 1 bar pressure and a temperature range of 25°C to 29°C. It was found that the H_2 enrichment could increase the biogas burning rate to a significant extent, especially at 30 - 40% enrichment. For smaller enrichment, i.e., at 10 - 20%, an increase in the burning rate is not significant and within the experimental error. The flammability limits of the biogas also widen upon 30% H_2 addition, suggesting an increase in the fuel concentration in the reaction zone. From the *Schlieren* images, it is shown that the flame was susceptible to the phenomenon of flame stability. The flame stability and burning rate seem to be enhanced at higher H_2 addition and equivalence ratio. This shows that the H_2 addition can overcome the dilution effect of CO_2 that tends to absorb the heat released during combustion resulting in reduced burning rate.

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