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LAMINAR BURNING VELOCITY AND FLAMMABILITY CHARACTERISTICS OF BIOGAS IN SPARK IGNITED PREMIX COMBUSTION AT REDUCED PRESSURE

Willyanto Anggono¹, ING Wardana², K. J. Hughes³, M. Lawes⁴, Slamet Wahyudi⁵, Nurkholis Hamidi⁶

¹Petra Christian University/ Mechanical Engineering Department, Surabaya, Indonesia. ¹Email: willy@petra.ac.id

^{1,2,5,6}Brawijaya University/ Doctoral Program Mechanical Engineering Department, Malang, Indonesia.

^{1,3}The University of Leeds/ School of Process, Environmental and Materials Engineering, Leeds, England.

⁴The University of Leeds/ School of Mechanical Engineering, Leeds, England.

Abstract

Biogas as a “Powergas” is an alternative fuel produced in digestion facilities, that is sustainable and renewable. Given it has a different composition to traditional fuels. A fundamental study of biogas flame propagation characteristics is desirable to quantify this important fuel property. Spherically expanding flames propagating at constant pressure are employed to measure the laminar burning velocity and flammability characteristics as mixture function of the mixture composition. These important parameters were measured using a photographic technique in a high pressure fan-stirred bomb. The characteristics of biogas-air flames were initially studied at reduced pressure and at various equivalence ratios from the lower flammable limit to the upper flammable limit. The results were compared with those from biogas-air flames at atmospheric pressure and also methane-air flames, both at reduced and atmospheric pressures. Based on this experimental investigation, the laminar burning velocities of biogas-air mixtures at reduced pressure were 0.2219 m/s for $\phi=0.75$, 0.2463 m/s for $\phi=0.80$ and 0.2705 m/s for $\phi=0.85$ respectively and only for these biogas mixtures propagated at reduced pressure. At the same equivalence ratio (ϕ), the laminar burning velocities of the biogas-air mixtures at reduced pressure is higher than those at atmospheric pressure, the flammable region of biogas becomes narrower in the presence of inhibitors (carbon dioxide and nitrogen) and the presence of inhibitors also causes a reduction in the laminar burning velocity. In addition, the flammable region of biogas became narrower by reducing initial pressure. The dilution effect is stronger at reduced pressure. Therefore, the flammable composition mixture areas of biogas-air mixtures are more limited at reduced pressure than those at atmospheric pressure. The inhibitor gases work more effectively in rich mixtures because the rich biogas-air mixtures have a higher fraction of carbon dioxide and nitrogen components compared to those for lean biogas-air mixtures.

Highlights

► A fundamental study of biogas laminar burning velocity and flammability characteristics is required before it can become a major sustainable fuel. ► The impact of impurities as inhibitors behavior in biogas on laminar burning velocity and flammability characteristics is understood better at reduced pressure ► At reduced pressure flammable region of biogas becomes narrower and its laminar burning velocities is higher than those at atmospheric pressure ► Inhibitors reduce the laminar burning velocity and make the flammable region narrower ► The dilution effect is stronger at reduced pressures.

Keywords

Biogas; Sustainable energy; Premixed combustion; Laminar burning velocity, Flammability characteristics.

Introduction

Biogas, an alternative fuel that is both sustainable and renewable is produced in digestion facilities. It does not contribute to the increase in atmospheric carbon dioxide concentrations because it comes from an organic source with a short carbon cycle and is a green solution in the development of sustainable fuels (Anggono et. al., 2012). Furthermore, the digestion facilities can be constructed quickly in a few days using unskilled labor (Lichtman et. al., 1996). Biogas contains 50–70% methane and 30–50% carbon dioxide, as well as small amounts of other gases and typically has a calorific value of 21–24 MJ/m³ (Bond and Templeton, 2011). Based on chemical analysis, the composition of the biogas produced in East Java is 66.4% methane, 30.6% carbon dioxide and 3% nitrogen (Anggono et. al., 2012). Methane is a flammable gas, whereas, nitrogen and carbon dioxide are inhibitors (Ilminnafik et. al., 2011). Following the Kyoto protocol, increasing efforts have made to find alternative, environmental friendly and sustainable fuels. Whereas much useful research has already been conducted into the use of biogas for cooking (stoves) and engines such as gas turbines, more needs to be done before it becomes an important replacement for fossil fuels (Lafay et. al., 2007; Nathan et. al., 2010; Porpatham et. al., 2008; Bond and Templeton, 2011; Alwis, 2002; Kurchania, 2010).

A fundamental study of biogas flame propagation characteristics is required before it can become a major sustainable fuel. Laminar burning velocity and flammability characteristics are both important parameters of a combustible mixture. Flammability limits give the proportion of combustible gases in a mixture, between which limits this mixture is flammable. Gas mixtures consisting of combustible, oxidizing, and inert gases are only flammable under certain conditions. The lower flammable limit describes the leanest mixture that still sustains a flame, i.e. the mixture with the smallest fraction of combustible gas, while the upper flammable limit gives the richest flammable mixture. In contrast to that of methane and the other hydrocarbon fuels, a fundamental study of biogas shows that the trend of laminar burning velocity changes as a function of the equivalence ratio (Anggono et. al., 2012). The laminar burning velocity of a rich biogas-air mixture is lower than that of a lean mixture. This reinforces the observation that the effect of inhibitor gases in biogas on laminar burning velocities is higher in rich mixtures than that in lean ones due to the higher mole fraction of these inhibitor gases. This is due to the fact that CO₂ in biogas dilutes the fuel mixtures and obstructs the reaction, and at the same time absorbs reaction heat thus further reducing the rate of reaction. The action of CO₂ resembles the effect of high pressure by increasing the diffusion and reducing the residence times of the reactant or by reducing the thermal diffusivity and increasing the reaction time. A better understanding on the role of CO₂ in biogas may be obtained from reducing the pressure where the diffusivity of the fuel mixtures is higher. Thus it is expected that the reaction time will be shorter. However, the laminar burning velocity of biogas at reduced pressure, as a fundamental characteristic of the fuel, has not been studied yet. Thus, the aim of this paper is to investigate its laminar burning characteristics at reduced pressure.

Demands for replacing fossil fuels in order to reduce emissions require an improved fundamental understanding of the combustion processes that occur within the internal combustion engine and an important characteristic is the burning velocity which directly affects pressure development and is often expressed in terms of laminar burning velocity (Anggono et. al., 2012; Gillespie et. al., 2000; Gu et. al., 2000; Bradley et. al., 1998; Serrano et. al., 2008; Marshall et. al., 2011). Laminar burning velocity is the most important flame propagation characteristic in spark ignited premixed combustion and as the fundamental flame propagation characteristic of biogas requires further study, this paper looks into this matter with view to a better understanding of a new alternative and renewable fuel. The results are compared with those from biogas-air flames at atmospheric pressure as well as methane-air flames at both reduced and atmospheric pressure to emphasize the contrast between the burning velocity of methane-air mixtures and biogas-air mixtures.

EXPERIMENTAL METHODS

The laminar burning velocity of biogas premixed combustion was measured in the Mk II high pressure fan-stirred combustion vessel at Leeds University School of Mechanical Engineering, as shown in Fig. 1. Initially, all the experiments in this paper were performed at room temperature, at reduced pressure (0.5 atm) and at various equivalence ratios (ϕ) from from the lower flammable limit to the upper flammable limit. The bomb is a spherical stainless steel vessel of 380 mm diameter, with three pairs of orthogonal windows each of 150 mm diameter and is equipped with four fans driven by electric motors (Anggono et. al., 2012; Gillespie et. al., 2000; Gu et. al., 2000; Bradley et. al., 1998; Serrano et. al., 2008).

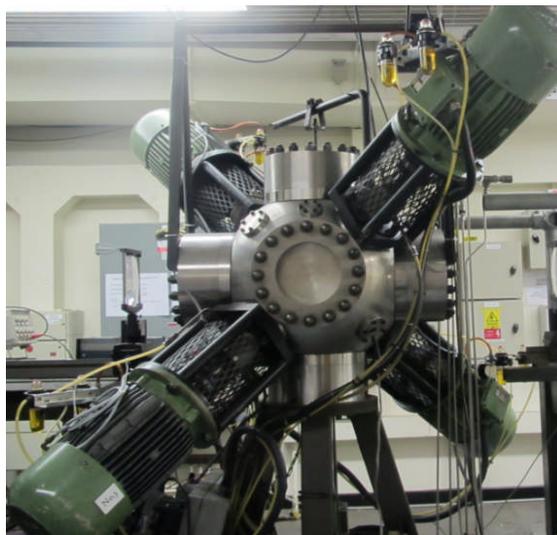


Figure 1. Mk2 Combustion Bomb

The fuel-air mixtures in the Mk II combustion bomb were centrally ignited and flame propagation was recorded by a high speed schlieren cine-photography using a Photsonics Phantom digital camera as shown in Fig. 2, operating at a rate of 2500 frames/s with a resolution of 768 x 768. The flame radius was calculated as that of a circle encompassing the same area as that enclosed by the schlieren imaged flame (Anggono et. al., 2012; Gillespie et. al., 2000; Gu et. al., 2000; Bradley et. al., 1998; Serrano et. al., 2008).



Figure 2. High Speed Schlieren Cine-Photography

The laminar burning velocity of a spherically expanding flame can be deduced from the schlieren photographs, the stretched flame velocity (S_n) can be derived from the flame radius versus time data as: $S_n = dr_u/dt$, where r_u is the flame radius in the Schlieren photographs and t is the elapsed time from spark ignition. The flame stretch rate α is defined as $\alpha = d(\ln A)/dt = (dA)/(A dt)$, where A is the area of the flame. In the case of a spherically propagating premixed flame, the flame stretch rate can be calculated by $\alpha = (2/r_u)(dr_u/dt)$. A linear relationship between flame speed and the total stretch exists, and this is quantified by burned gas of Markstein length, L_b , and is defined at the radius, r_u , such that: $S_n - S_s = L_b \alpha$, where S_s is the unstretched flame speed, and is obtained as an intercept value of S_n at $\alpha = 0$ in the plot of S_n against α . The gradient of the best straight line fit to the experimental data gives L_b . The unstretched laminar burning velocity, u_l , was deduced from S_s using $u_l = S_s (\rho_b/\rho_u)$, where ρ_b is the density of the burned gas mixtures and ρ_u is the density of the unburned gas mixtures (Anggono et. al., 2012; Gillespie et. al., 2000; Gu et. al., 2000; Bradley et. al., 1998; Serrano et. al., 2008).

RESULTS AND DISCUSSION

Based on this experimental investigation at various equivalence ratios from the lower flammable limit to the upper flammable limit, the flames were propagated for lean ($\phi=0.75$, $\phi=0.80$, $\phi=0.85$) biogas-air mixtures at reduced pressure as shown in Table 1 and these mixtures are the only biogas-air mixtures propagated at reduced pressure. The images obtained from the spherical flame propagation within the combustion bomb are shown in Fig. 3.

Table 1. Laminar Burning Velocities of Biogas-Air Mixtures Results at Reduced Pressure

Biogas, pressure = 0.5 Atm	
ϕ	Laminar burning velocity (m/s)
$\phi=0.60$	No Propagation
$\phi=0.70$	No Propagation
$\phi=0.75$	Propagated
$\phi=0.80$	Propagated
$\phi=0.85$	Propagated
$\phi=0.90$	No Propagation
$\phi=1.00$	No Propagation

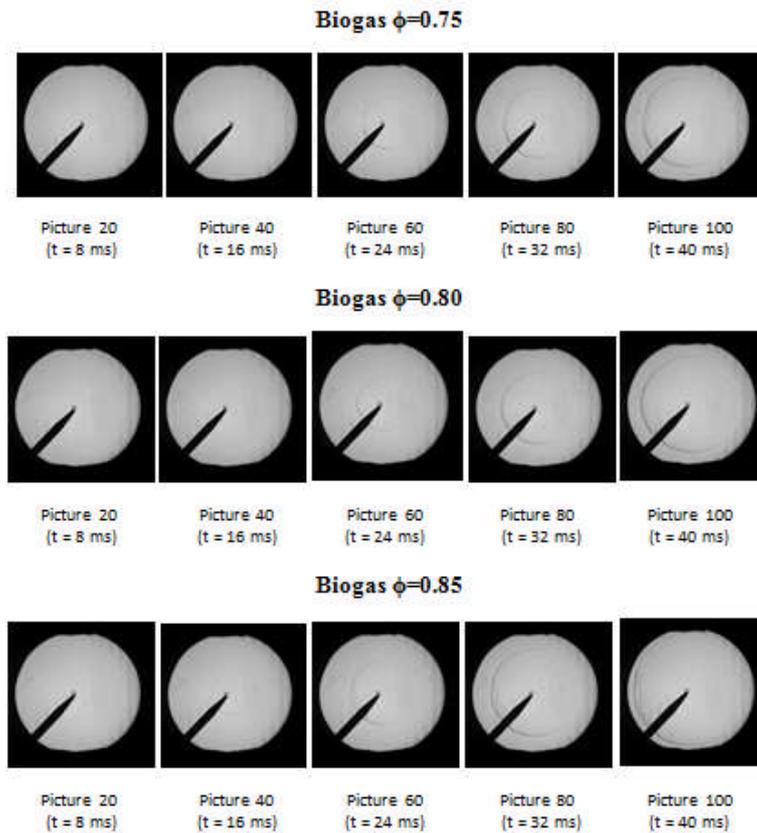


Figure 3. Biogas Flame Propagation at Various Equivalence Ratios under Reduced Pressure

The radius of the spherical flame propagation biogas-air mixtures at reduced pressure in Fig. 3 are presented in Fig. 4 as a function of elapsed time. Based on the experimental results and the calculations, as mentioned in the experimental method and in the previous studies (Anggono et. al., 2012; Gillespie et. al., 2000; Gu et. al., 2000; Bradley et. al., 1998; Serrano et. al., 2008), the laminar burning velocities of lean biogas-air mixtures in premixed combustion at reduced pressure are 0.2219 m/s for $\phi=0.75$, 0.2463 m/s for $\phi=0.80$ and 0.2705 m/s for $\phi=0.85$ respectively.

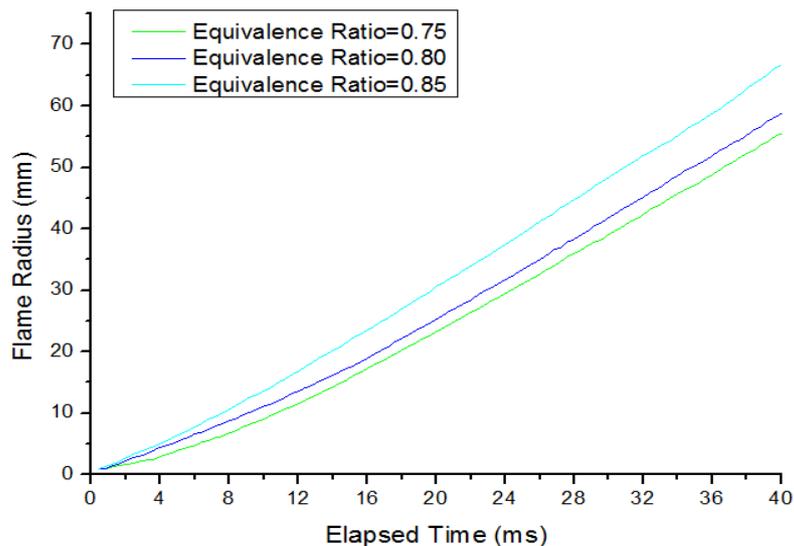


Figure 4. Flame Radius vs Elapsed Time of Biogas-Air Mixtures

Based on the results of the experiments at reduced pressure, biogas flame propagates only in a very narrow range of equivalent ratio, from $\phi=0.75$ till $\phi=0.85$. For methane, the flame propagates at wider range of equivalent ratio, that is, from $\phi=0.7$ till $\phi=1.0$.

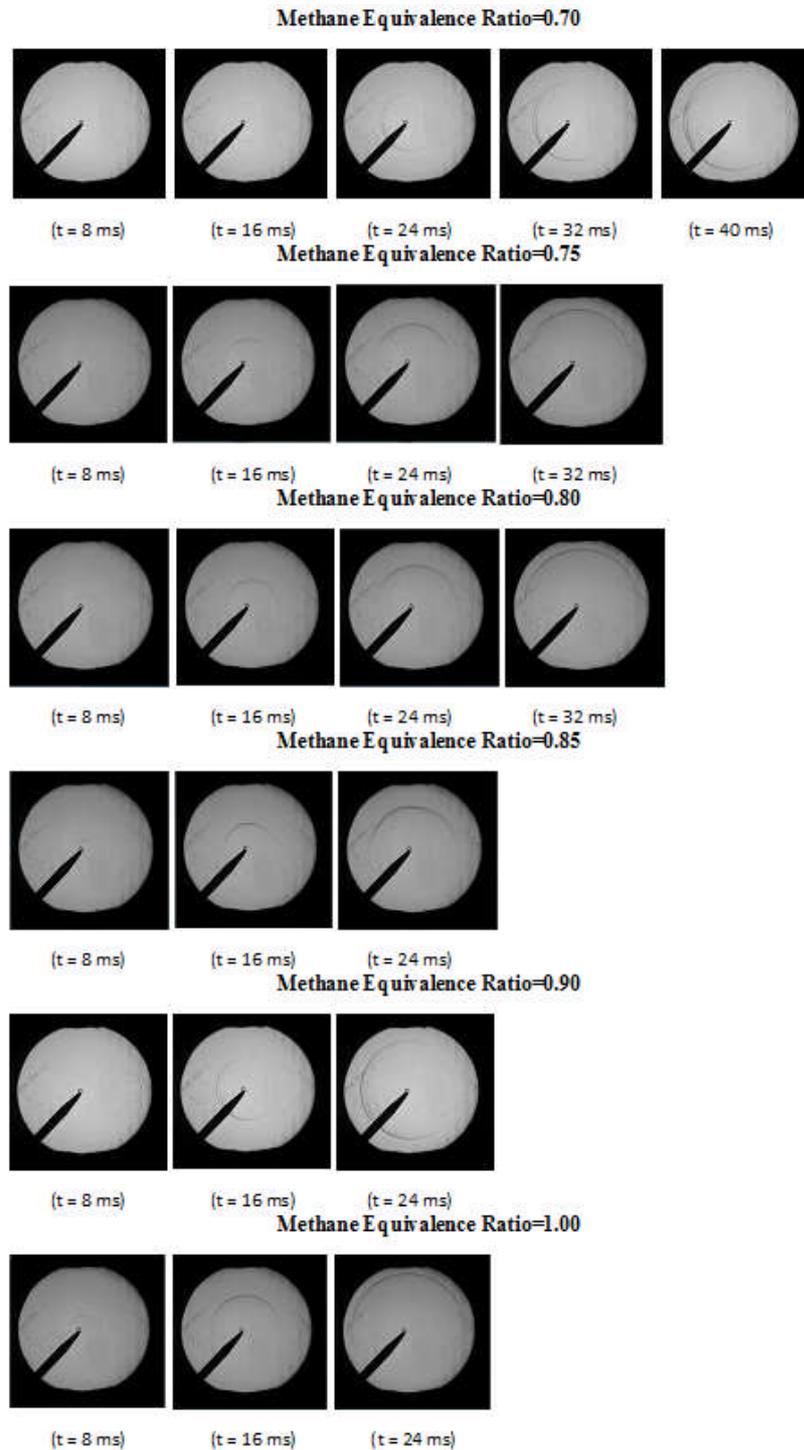


Figure 5. Methane Flame Propagation at Various Equivalence Ratios at Reduced Pressure

For better understanding, the results from previous study (Anggono et. al., 2012) on the laminar burning velocities of biogas and methane at room temperature, atmospheric pressure and various equivalence ratios (ϕ) are also presented in Table 2. Based on the same experimental procedure and calculations as mentioned in previous studies (Anggono et. al., 2012; Gillespie et. al., 2000; Gu et. al., 2000; Bradley et. al., 1998; Serrano et. al., 2008), the results on laminar burning velocities of the methane-air premixed mixtures at reduced pressure are presented in Table 3, and the combined Table 2 and Table 3 data are plotted in Fig. 6.

Table 2. Laminar Burning Velocities of Methane and Biogas at Atmospheric Pressure (Anggono, 2012)

Methane, pressure = 1 Atm		Biogas, pressure = 1 Atm	
ϕ	Laminar burning velocity (m/s)	ϕ	Laminar burning velocity (m/s)
0.5	No propagation	0.5	No propagation
0.6	0.0948	0.6	0.0743
0.8	0.2749	0.8	0.2086
1.0	0.3527	1.0	0.2638
1.2	0.3082	1.2	0.1864
1.3	0.2015	1.3	No propagation
1.4	No propagation	1.4	No propagation

Table 3. Laminar Burning Velocities of Methane and Biogas at Reduced Pressure

Methane, pressure = 0.5 Atm		Biogas, pressure = 0.5 Atm	
ϕ	Laminar burning velocity (m/s)	ϕ	Laminar burning velocity (m/s)
$\phi=0.60$	No Propagation	$\phi=0.60$	No Propagation
$\phi=0.70$	0.2339	$\phi=0.70$	No Propagation
$\phi=0.75$	0.2872	$\phi=0.75$	0.2219
$\phi=0.80$	0.3184	$\phi=0.80$	0.2463
$\phi=0.85$	0.3522	$\phi=0.85$	0.2705
$\phi=0.90$	0.3785	$\phi=0.90$	No Propagation
$\phi=1.00$	0.4150	$\phi=1.00$	No Propagation
$\phi=1.20$	No Propagation	$\phi=1.20$	No Propagation
$\phi=1.30$	No Propagation	$\phi=1.20$	No Propagation
$\phi=1.40$	No Propagation	$\phi=1.20$	No Propagation

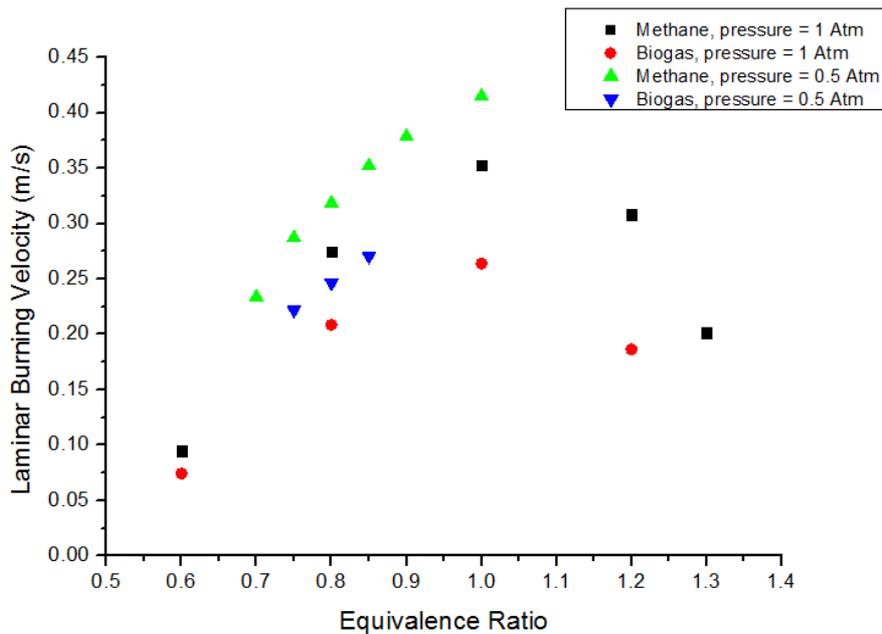


Figure 6. Laminar Burning Velocities of Methane-Air Mixtures and Biogas-Air Mixtures

The flame for methane-air mixtures at atmospheric pressure can propagate between $\phi=0.6$ and $\phi=1.3$. Above $\phi=1.3$, the flame extinguishes because the combustion reaction was quenched by the larger mass of fuel. At $\phi<0.6$, the flame also vanishes because the reaction heat energy was insufficient to burn the mixture. The flame for biogas-air mixtures at atmospheric pressure propagates over a narrower range between $\phi=0.6$ and $\phi=1.2$. At $\phi>1.2$, the flame does not propagate because of two reasons: the combustion reaction is quenched by the larger mass of fuel and some of the heat energy is absorbed by inhibitors that strengthen the quenching effect. At $\phi<0.6$, the flame cannot propagate because the reaction heat energy is insufficient to burn the mixture. Compare to a methane-air mixture, the presence of carbon dioxide and nitrogen in the biogas caused a reduction in the laminar burning velocity for two reasons. First, the dilution effect leads to a lower concentration of reactive species in the fuel-air mixtures for a given equivalence ratio, which leads in turn to a lower overall chemical reaction rate in the bimolecular reactions in the fuel oxidation reaction process. Secondly, the presence of these additional inhibitor gases absorbed some of the heat generated, thus lowering the flame temperature which in turn tends to reduce the overall rate of many of the chemical reactions within the fuel oxidation process. The effect of inhibitor gases is stronger in rich mixtures because the rich biogas-air mixtures have a higher

fraction of the carbon dioxide and nitrogen components compared to lean biogas-air mixtures. The laminar burning velocities at reduced pressure are higher than those at atmospheric pressure. This is due to the effects of low pressure that reduces the diffusion time and increases the residence times of the reactant or increases the thermal diffusivity and reduces the reaction time which in turn increases the laminar burning velocity. The trend is consistent with the higher laminar burning velocity at lower pressure reported by (Gu et al., 2000).

Methane flame at reduced pressure, as shown in Fig. 6, propagates in a narrower range of ϕ , i.e., from $\phi=0.7$ to $\phi=1.0$. This is due to the fact that the fuel fraction is lower at reduced pressure. Therefore, the reaction heat energy which is lower is now insufficient to burn the fuel mass at $\phi<0.7$ and it is quenched stronger at $\phi>1.0$. For biogas, the flame propagates in a very narrow range of equivalence ratio, i.e., from $\phi=0.75$ to $\phi=0.85$. In this case, the inhibitors in biogas dilutes more the fuel mixtures that obstructs the reaction stronger and at the same time absorbs the reaction heat energy, thus the very low reaction heat energy is only sufficient for burning fuel mixtures in a very narrow range of equivalence ratio.

To summarise, the reduced pressure on the one hand increases the residence time of biogas fuel that increases the laminar burning velocity, but on the other hand the inhibitors in the fuel dilutes more the reactant and at the same time absorbs the reaction heat energy that strongly restricts the flammability limit.

CONCLUSION

Compared to a methane-air mixtures, in the biogas-air mixtures, the presence of carbon dioxide and nitrogen cause a reduction in the laminar burning velocity for two reasons, First, the dilution effect lead to a lower concentration of reactive substances in the fuel-air mixture for a given equivalence ratio, which lead to a lower overall chemical reaction rate in the bimolecular reactions in the fuel oxidation reaction process. Secondly, the presence of inhibitor gases absorbed some of the heat generated, thus lowering the flame temperature which in turn tended to reduce the overall rate of many of the chemical reactions within the fuel oxidation process. At reduced pressure, the diffusion time of reactant decreases so that the resident time of reactant become longer. Consequently, the laminar burning velocity become higher than that at atmospheric pressure. The fuel fraction of biogas at reduced pressure is lower. Therefore, the dilution effect of inhibitors in the fuel become stronger. As a result obstruction of reaction by inhibitors is stronger. At the same time, the heat energy from the reaction is absorbed by the inhibitors. The resultant of these effects makes the flammability limit of biogas at reduced pressure becomes very narrow. The effect of inhibitor gases is stronger at rich mixtures because the rich biogas-air mixtures have a higher fraction of carbon dioxide and nitrogen components compared to the lean biogas-air mixture. Furthermore, to make biogas as a sustainable and renewable fuel in transportation area, study of biogas flame propagation characteristics at high pressure and engine experiments is required.

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