Behaviour of Biogas Containing Nitrogen on Flammability Limits and Laminar Burning Velocities

Willyanto Anggono*‡

*Mechanical Engineering Department, Petra Christian University, Surabaya, Indonesia, 60236

*Centre for Sustainable Energy Studies, Petra Christian University, Surabaya, Indonesia, 60236

(willy@petra.ac.id)

‡ Corresponding Author: Willyanto Anggono, Mechanical Engineering Department, Petra Christian University, Surabaya, Indonesia, 60236, Tel:+62 31 8439040, Fax: +62 31 8436418, willy@petra.ac.id

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Abstract- Biogas is a renewable energy and consists of up to 50% methane (CH_4) as a flammable gas (pure flammable biogas/ inhibitorless biogas) and other impurities such as nitrogen (N_2) up to 10%, the second biggest impurity in it. Before it can be used as a substitution for fossil fuels, a basic understanding of its combustion processes in spark ignited combustion engines is needed. This research focused on the biogas containing nitrogen flammability limits and laminar burning velocities at various pressure. Biogas containing N_2-dry air mixtures was burned in a 380mm bomb spherical bomb with spark ignition in the centre of the vessel (bomb). The spherical bomb was employed for this research, gases in various mixtures were injected into it by an absolute pressure transducer at pressures appropriate for the equivalence ratios required. Then, dry air was pumped in at the pressures needed. Biogas mixtures were centrally ignited and the propagated flame was recorded with a high speed camera. All biogas mixtures experiments were performed at ambient temperatures under different pressures as well as at different equivalence ratios. The findings were contrasted to the outcomes of prior study into pure flammable biogas. The outcomes indicated that the lesser the amount of N_2 in biogas, the greater the laminar burning velocities. And furthermore, that when initial pressures were reduced and equivalence ratios were the same, laminar burning velocities increased and that increasing N_2 levels at the same initial combustion pressures did not influence to the flammability limits of biogas.

Keywords Flammability limit, sustainable energy, laminar burning velocity, biogas, nitrogen.

1. Introduction

Biogas, a renewable and sustainable fuel that is alternative and substitute fuel is created in digestion facilities employing anaerobic fermentation of organic material [1-5]. Previous worldwide energy crisis has focused attention on alternative sources of energy to fossil fuels. However, achieving solutions to this problem of finding economical and sustainable alternative sources of energy, as well as reducing pollutants that cause global warming, will not be easy. And biogas, a colourless flammable gas produced by anaerobic digestion consisting of methane, carbon dioxide, nitrogen and small amounts of other gases, would seem to be a renewable energy source that has much potential and being a by-product of both animal/ human waste and plant decomposition it should both economical and practical [1-6]. Inert gases act as impurities, substances which reduce laminar burning velocities. The laminar burning velocity become higher at 0.5 atm than those at 1 atm and the flammable area between lower flammability limit and higher flammability limit of biogas at atmospheric pressure (1 atm) becomes wider than those at reduced pressure (0.5 atm) [3,4,7,8]. Severel previous studies showed that carbon dioxide effects biogas laminar burning velocities, flammability limits, flame characteristics and the emissions in combustion products. It effects both in external and internal combustion [9-13]. The other previous study also showed that nitrogen effects biogas combustion by reducing its flame speed and nitrogen can decrease the biogas combustion rate [14]. Nevertheless, the effects of nitrogen as the second biggest impurities on biogas flammability limits and laminar velocities have not yet been investigated in depth.

Combustion can be specified as an exothermic chemical reaction between an oxidizer and fuel sparked by an igniter. In this research biogas containing nitrogen was the fuel and dry air was the oxidizer agent and sparks was the igniter. The equivalence ratio (ϕ) was used to determine whether the stoichiometric fuel-oxidant mixture was lean (ϕ<1), stoichiometric (ϕ=1) or rich (ϕ>1). The stoichiometric condition has benefits for various specific applications which also improve thermal efficiency and reduce exhaust emissions. For most fuels, rich mixtures have higher speeds than lean ones. The fuel component of biogas is methane which has similar characteristics to hydrocarbon fuels such as methane and natural gas and have the same ability to reach high temperatures on combustion but with fewer emissions [3-9,12-13,15-25].

With the rising consumption and cost of hydrocarbon fuels, cheaper alternative sources can bring significant economic benefits to developing countries like Indonesia. This study was enacted to gain more insight into biogas flammability limits and biogas laminar burning velocities as the main characteristics of biogas combustion processes and the effect of nitrogen as the second biggest impurities on biogas flammability limits and laminar velocities. The flammable portion of biogas is methane which has environmental and technical advantages over fossil fuels in that, on combustion it reaches high temperatures yet it emits less harmful contaminants and greenhouse gases [3-4]. Flammability levels indicate biogas's proportion of combustible gases and their limits and its components consist of both combustible, oxidizing inert elements. The leanest ignitable flammable mixture is the one with the least amount of combustible gases; likewise, the richest one has the highest flammable limit [3,4,7,8,12].

Biogas differs from other hydrocarbon fuels in that studies have shown that ϕ (equivalence ratio) influence to the burning velocity, and that impurity gases have a greater influence on burning velocities in lean mixtures and a correspondingly lesser effect on rich mixtures due to their higher more factor. This occurs because impurities not only dilute fuel mixtures but also impede reactions as well as absorbing reaction heat which further reduce reaction rates. The effects of impurities are similar to those of high pressures which cut short reactant resident times, raise diffusion times or by reducing pressures when normal thermal diffusivity of fuel mixtures is higher, which in turn shortens reaction times [4,7-9,12].

The flame diffusion contributes a crucial part in the accomplishes of the combustion ignition process; for example, data on burning velocities can be used to determine the materials used to construct internal combustion chambers and other parts that are directly involved with the combustion chamber during an explosion. Theoretically, biogas combustion creates a compression wave which compresses the mediums in front of the flame front surfaces, and this chemical reaction causes the rapid expansion of the flames. And the results of this rise in pressure, density and temperature suddenly form a detonating wave [4,8,12].

2. Experimental Methods

Biogas containing various N_2 (nitrogen) laminar burning velocities were investigated in Mk2 spherical combustion bomb with spark ignition in the centre of the bomb (vessel). All the experiments were performed at Bradley combustion laboratory, School of Mechanical Engineering, University of Leeds. The spherical bomb was fulled with biogas containing N_2-dry air mixtures of differing compositions (5% and 10%) of nitrogen. All experiments were performed at ambient temperatures under different pressures, 0.5 atm (reduced pressure) and 1 atm (atmospheric pressure) as well as at different equivalence ratios (ϕ) from lower flammability limits to upper flammability limits. Experiment results were compared to those from our previous studies of methane at equivalence ratios and various pressures. The Mk2 spherical combustion bomb with spark ignition in the centre of the bomb (vessel) is shown in Fig. 1 and the experimental system diagram is shown in Fig. 2. Before supplying the vessel with the biogas-dry air mixtures gas, a vacuum was created in the vessel and the variation of the equivalence ratios ranged from lower flammability limits to upper flammability limits.

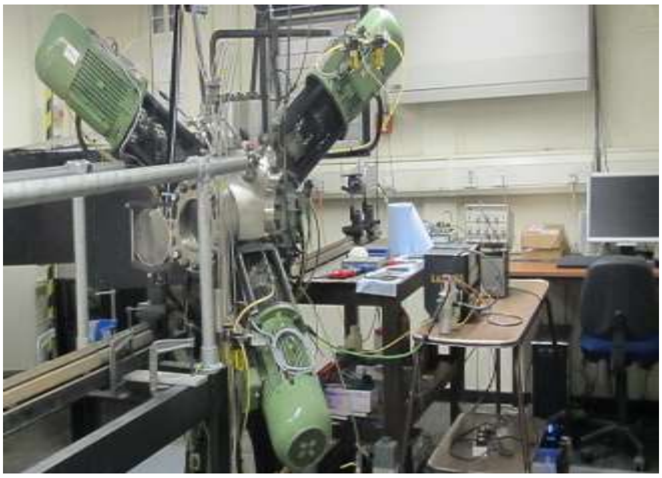

Fig. 1. Mk2 spherical combustion bomb system with spark ignition in the centre of the bomb

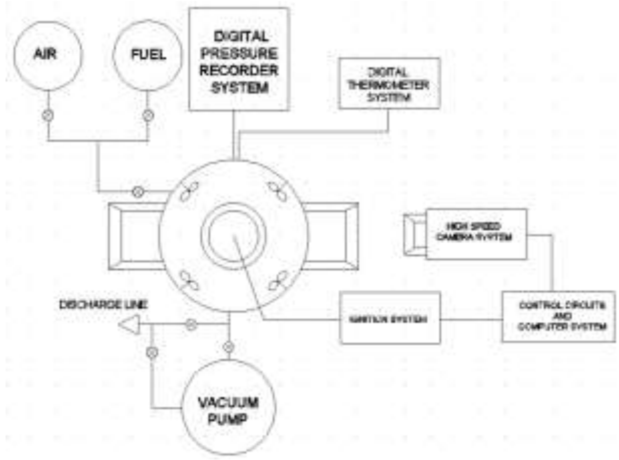

Fig. 2. The experimental system diagram

Fig. 3. 380mm diameter of Mk2 spherical bomb

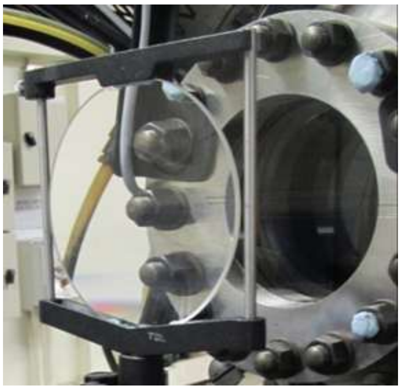

Fig. 4. 150mm diameter window of Mk2 spherical bomb

A 380mm diameter spherical bomb as shown in Fig. 3 with 150mm diameter windows as shown in Fig. 4 and is equipped with four electric motor fans was employed for this research, gases in various mixtures were injected into it by an absolute pressure transducer at pressures appropriate for the equivalence ratios required. Then, dry air was pumped in at the pressures needed and the biogas containing N_2-dry air mixtures were centrally ignited and the propagated flame was recorded by a high speed (2500 frames/s) camera. The procedures to obtain the laminar burning velocity were gathered from the high speed camera can be obtained in the several prior studies [3,4,7,8,12,24-27].

3. Results and Discussion

Biogas containing 5% N_2-dry air mixtures produced propagating flames at atmospheric pressure for the 0.6, 0.8, 1.0, 1.2 and 1.3 equivalence ratios. The mixtures were centrally ignited and the resulting flame propagation recorded at 2500 frames/ second by a high speed camera through the window and laid out in Fig. 5.

At atmospheric pressure (1 atm) and ambient temperatures, no flames were propagated from the rich ($\phi \geq 1.4$) and lean ($\phi \leq 0.5$) biogas-dry air mixtures and the flammable areas of the biogas with 5% N_2-dry air mixtures at atmospheric pressure and ambient temperatures were 0.6 to 1.3 equivalence ratios. The ϕ=0.6 was the lower flammability limit and the ϕ=1.3 equivalence ratio was the higher flammability limit. Based on our several previous research determined the laminar burning velocities [3,4,7,8,12,24-27], the biogas containing 5% N_2-dry air mixtures laminar burning velocities at 1 atm are laid out in Table 1.

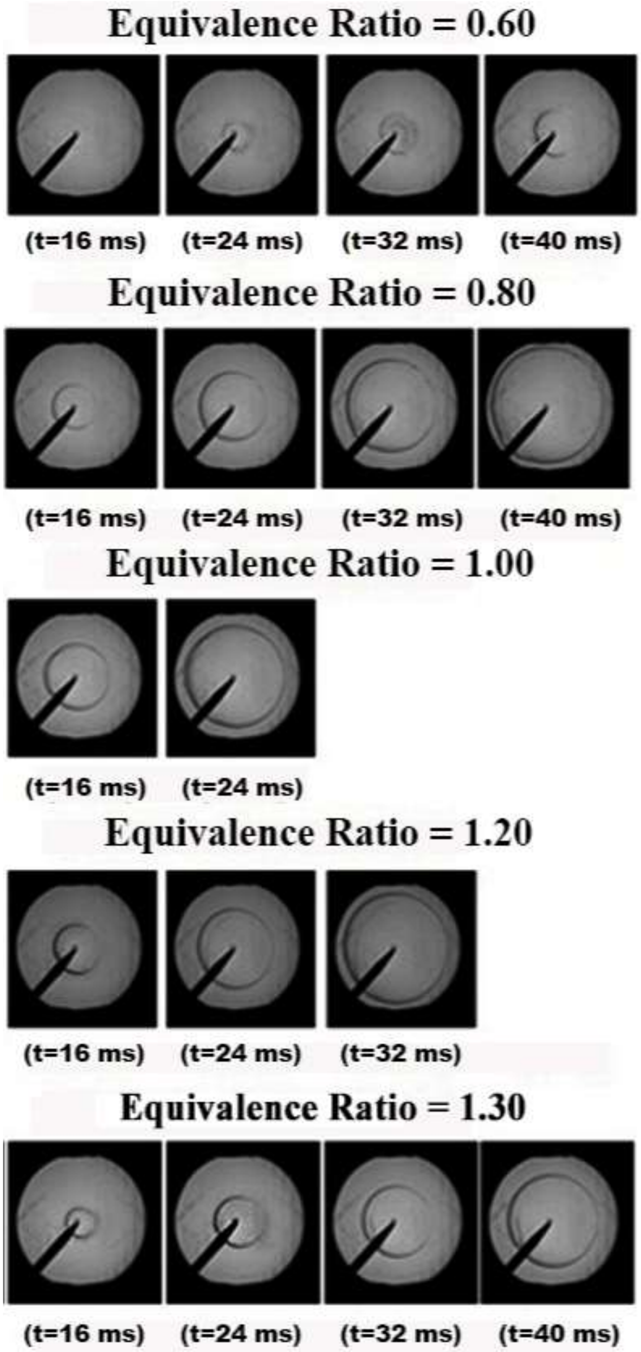

Fig. 5. Biogas containing 5% N_2 flame propagation at 1 atm

Table 1. Biogas containing 5% N_2 laminar burning velocities at 1 atm

ϕ	Laminar Burning Velocity (m/s)
0.5	No Propagation
0.6	0.093
0.8	0.269
1.0	0.345
1.2	0.298
1.3	0.193
1.4	No Propagation

The biogas mixtures containing 10% N_2-dry air mixtures produced propagating flames at ambient temperature and 1 atm for 0.6, 0.8, 1.0, 1.2 and 1.3 (equivalence ratios). At atmospheric pressure and ambient temperatures no flames were produced from the rich ($\phi \geq 1.4$) and lean ($\phi \leq 0.5$) biogas-dry air mixtures. The spherical flame flaring images within the combustion chamber are laid out in Fig. 6.

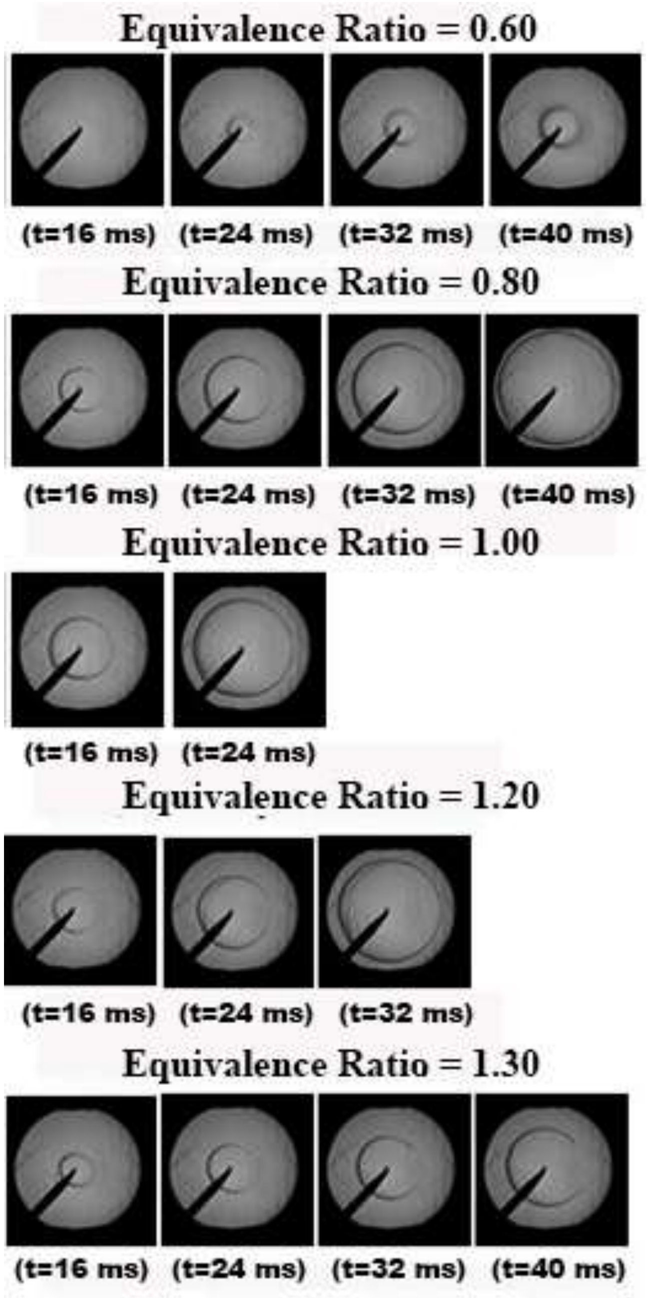

Fig. 6. Biogas containing 10% N_2 flame propagation at 1 atm

Flammable areas of biogas with 10% N_2-dry air mixtures at atmospheric pressure and ambient temperatures were from 0.6 to 1.3 equivalence ratios. The 0.6 equivalence ratio was the lower limit and the 1.3 one the upper flammability limit. Based on our previous experiments into obtaining laminar burning velocities [3,4,7,8,12,24-27], the biogas containing 10% N_2-dry air mixtures laminar burning velocities at 1 atm are shown in Table 2.

Table 2. Biogas containing 10% N_2 laminar burning velocities at 1 atm

Φ	Laminar Burning Velocity (m/s)
0.5	No Propagation
0.6	0.090
0.8	0.266
1.0	0.338
1.2	0.291
1.3	0.183
1.4	No Propagation

The biogas with 5% N_2-dry air mixtures produced propagating flames at 0.5 atm (reduced pressure) for the equivalence ratios of 0.7 to 1.0. At ambient temperatures and reduced pressure, no flames were propagated from the rich ((ϕ=1.2, ϕ=1.3 and ϕ=1.4) or lean (ϕ=0.5 and ϕ=0.6) mixtures. The 0.7 equivalence ratio was the lower flammability limit and the 1.0 equivalence ratios was the higher flammability limit. The spherical flame flaring images are shown in Fig. 7.

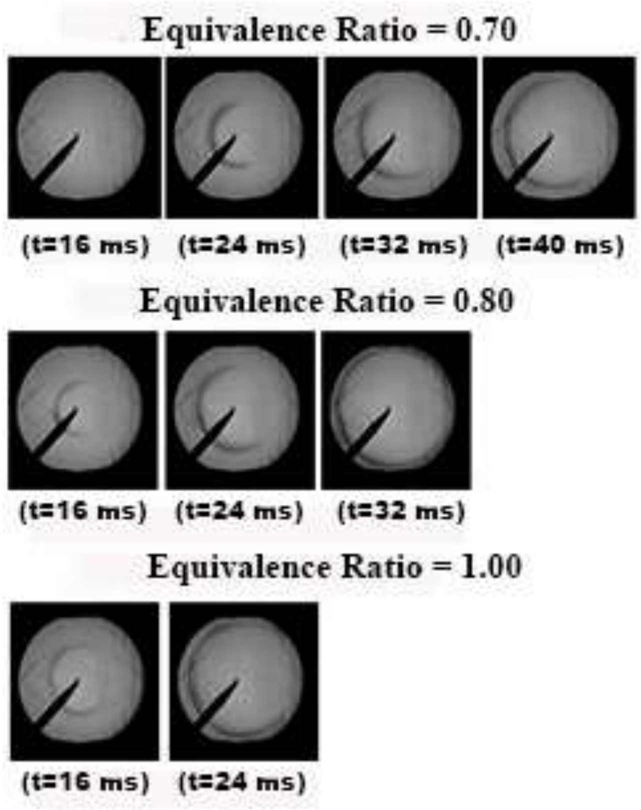

Fig. 7. Biogas containing 5% N_2 flame propagation at 0.5 atm

Based on our several previous studies into laminar burning velocities [3,4,7,8,12,24-27], the biogas containing 5% N_2-dry air mixtures laminar burning velocities at 0.5 atm are shown in Table 3.

Table 3. Biogas containing 5% N_2 laminar burning velocities at 0.5 atm

ϕ	Laminar Burning Velocity (m/s)
0.5	No Propagation
0.6	No Propagation
0.7	0.230
0.8	0.311
1.0	0.403
1.2	No Propagation
1.3	No Propagation
1.4	No Propagation

The biogas with 10% N_2-dry air content produced propagating flames at 0.5 atm (reduced pressure) for the equivalence ratios 0.7 to 1.0 at ambient temperatures and reduced pressures no flames were produced from the rich ((ϕ=1.2, ϕ=1.3 and ϕ=1.4) or lean (ϕ=0.5 and ϕ=0.6) mixtures. The spherical flame flaring images in the combustion chamber are presented in Fig. 8.

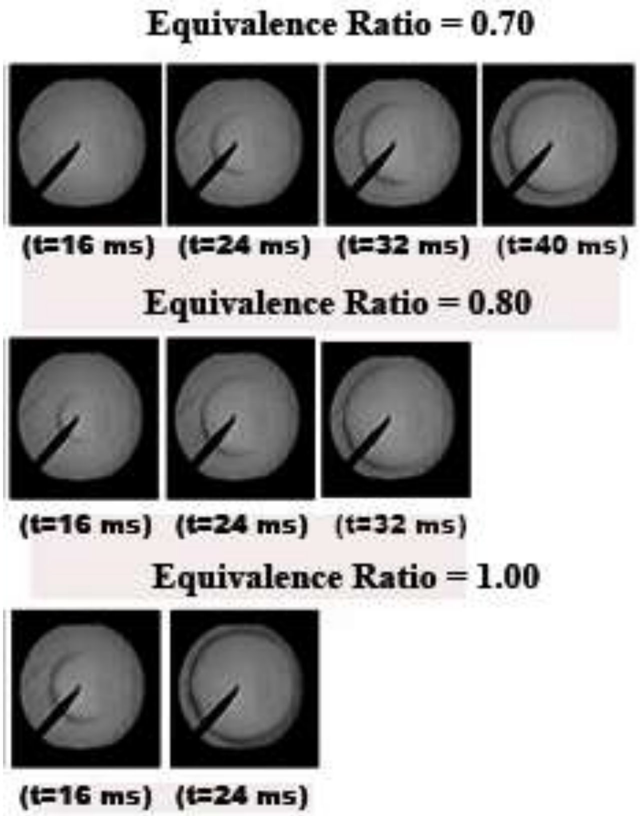

Fig. 8. Biogas containing 10% N_2 flame propagation at 0.5 atm

The flammability areas of the biogas with 10 % N_2-dry air mixtures at reduced pressure and ambient temperatures were from 0.7 to 1.0 equivalence ratios the 0.7 equivalence ratio was the lower flammability limit and the 1.0 the upper one. Based on our previous studies into laminar burning velocities [3,4,7,8,12,24-27], the biogas containing 10% N_2-dry air mixtures laminar burning velocities at 0.5 atm are laid out in Table 4.

Table 4. Biogas containing 10% N_2 laminar burning velocity at 0.5 atm

ϕ	Laminar Burning Velocity (m/s)
0.5	No Propagation
0.6	No Propagation
0.7	0.227
0.8	0.300
1.0	0.391
1.2	No Propagation
1.3	No Propagation
1.4	No Propagation

For better understanding, a summary of all experiments biogas containing N_2-dry air mixtures experiments results at ambient temperatures under different pressures, 0.5 atm and 1 atm as well as at different equivalence ratios (ϕ) from lower flammability limits to upper flammability limits. The outcomes were also comparered to biogas without impurity (pure flammable biogas) under various pressures, 0.5 atm and 1 atm as well as at different equivalence ratios (ϕ) from lower flammability limits to upper flammability limits are presented in Fig. 9.

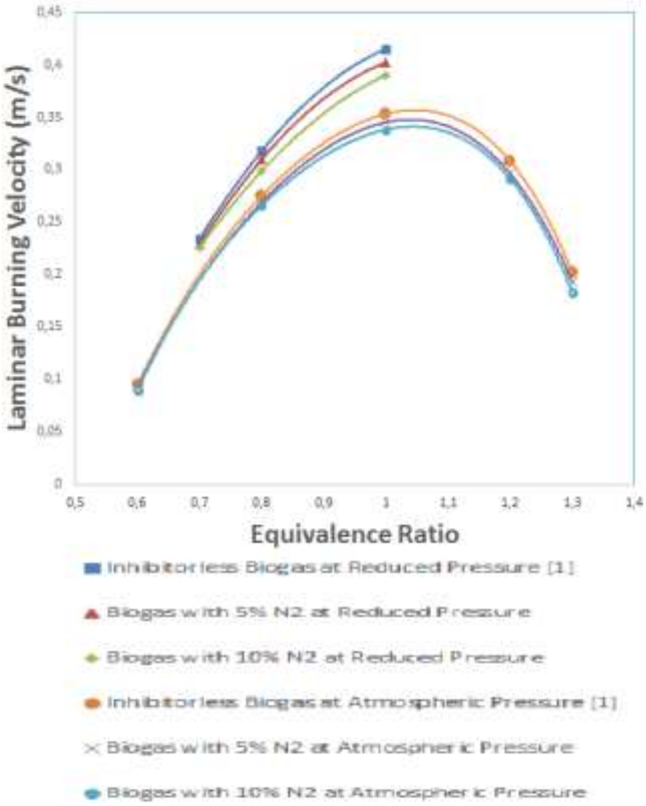

Fig. 9. Biogas containing various N_2 concentration flammability limits and laminar burning velocities characteristics

Nitrogen (N_2) slows laminar burning velocities by diluting concentration of the reactive elements for specified equivalence ratios as well as by absorbing heat and thus reducing both flame temperatures and chemical reaction rates and this effect becomes more pronounced at higher levels of nitrogen. The effect of N_2 is weaker in lean biogas containing N_2-dry air mixtures. The amount of inert gas dilution can be determined by dilution ratio is defined as: Zdilt=[Impurity]/([Impurity]+[dry air]), where [Impurity] and [dry air] denote the mole number of impurity component and dry air in the mixtures. Ratio of dilution is defined as the function ϕ of because the biogas which the higher the ϕ, the higher the ratio of dilution. It indicates that the rich mixture is diluted by much amount of impurities. Therefore, the flame characteristics biogas containing N_2-dry air mixtures in the lean mixtures were not changed drastically because of small amount of impurities. On the other hand, flame kernel quenching may be caused by the large amount of dilution in the case of rich mixtures.

Laminar burning velocities at atmospheric (1 atm) condition were lower than those at 0,5 atm (under atmospheric pressure) condition. The tendency is coherents with the higher pressure condition was decreased the laminar burning velocity [7-9,12]. Biogas containing N_2 at under atmospheric pressure (reduced pressure) has a very narrow range ϕ area betweeen lower flammablity limits and higher flammability limits, those are at ϕ=0.7 to ϕ=1.0 as shown in Fig. 9. The number of impurities in biogas containing N_2-dry air mixtures dilutes more fuel mixtures in the biogas that absorbs the heat energy obstructs the stronger reaction, thus the reaction energy was just sufficient for burning biogas containing N_2-dry air mixtures in a limited ϕ (equivalence ratio) range. When initial pressures were reduced and equivalence ratios were the same, laminar burning velocities increased and that increasing nitrogen levels at the same initial combustion pressures did not influence to the flammability limits of biogas.

4. Conclusion

The lesser the quantity of N_2, the greater the burning velocities of the mixtures. Furthermore, when initial pressures were reduced and equivalence ratios were the same, laminar burning velocities increased and that increasing nitrogen levels at the same initial combustion pressures did not influence the flammability limits of biogas. Nitrogen reduce laminar burning velocities by diluting the active parts of biogas-dry air mixtures in predetermined equivalence ratios, and also absorbs some of the heat thus decreasing flame temperatures and chemical reaction rates. The higher its content the greater the effect of N_2. At lower pressures, laminar burning velocities are higher because lower pressures reduce diffusion times but raise both residence times and thermal diffusivity which consequently lowers reaction times and therefore increase laminar burning velocity. The higher the ϕ (equivalence ratio), the higher the dilution ratio. It denotes that the rich mixture is diluted by much amount of impurities. Therefore, in the rich mixture condition, the characteristics of flame changed drastically because of huge amount of impurities.

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