

## EXPERIMENTAL AND NUMERICAL SIMULATION ON BIOGAS FLAME PROPAGATION CHARACTERISTIC IN SPARK IGNITION PREMIXED COMBUSTION

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**Abstract**—Biogas is a sustainable and renewable fuel that is produced in digestion facilities. Biogas can be utilized to replace energy derived from fossil fuels, and hence reduce emissions of greenhouse gasses. Based on the chemical composition analysis, the composition of biogas produced in East Java, Indonesia consists of 66.4% methane, 30.6% carbon dioxide and 3% nitrogen. Demands for improved engine design and replacing fossil fuels, in terms of power output, efficiency and emissions control, require improved fundamental understanding of the combustion processes that occur within the cylinder. The most importance characteristic is the burning velocity, which directly affects pressure development and often is expressed in terms of laminar burning velocity. The laminar burning velocity is the most important flame propagation characteristic in spark ignition premixed combustion. The experimental laminar burning velocity of biogas premixed combustion was measured in a high pressure fan-stirred bomb. Analysis based on careful photographic observation has been used to determine precisely defined (unstretched) laminar burning velocities. The numerical simulation has been done using the Premix module of CHEMKIN. The reaction mechanism used is GRI Mech 3.0 consisting of 325 elementary chemical reactions and associated rate coefficient expressions and thermochemical parameters for the 53 species involved in them. Based on the experimental investigation and the numerical simulation, the unstretched laminar burning velocity as the important characteristic of flame propagation in biogas premixed combustion has been found for initial conditions of a stoichiometric at room temperature and atmospheric pressure. Finally, The laminar burning velocity of biogas is better than pure methane in lean and rich mixtures at room temperature and atmospheric pressure initial conditions. Biogas has a good premixed combustion flame propagation characteristic and could be an alternative to replace the fossil fuels.

**Keywords**—Sustainable energy; Flame propagation; Biogas; Premixed combustion; Laminar burning velocity.

### I. INTRODUCTION

Sustainable development is an integral concept for achieving quality of life, interdependence, fundamentals and equity. Sustainable product development is defined as resource, context and future oriented product development, aimed at the fulfilment of elementary needs, better quality of life, equity and environmental harmony [15]. Based on the principal of sustainable product development, biogas is a sustainable product.

Biogas is a sustainable, renewable and green energy (product) that produced in digestion facilities. The consumption of fossil fuels in internal combustion engines and the associated environmental impacts are now the worldwide concerns. These concerns have stimulated researchers into more environmentally friendly alternative fuels that can replace the use of fossil fuels. Biogas as “Powergas” is one of these alternative fuels. The target of using biogas are: diversification of energy supply, reduction of CO<sub>2</sub> (carbon dioxide) emissions and contribute to rural development.

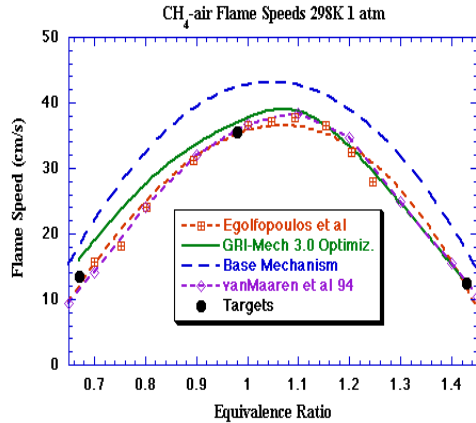
Biogas can be utilized to replace energy derived from fossil fuels, and hence reduce emissions of greenhouse gasses. Biogas does not contribute to increasing atmospheric carbon dioxide concentrations because the gas is not released directly into the atmosphere and the carbon dioxide comes from an organic source with a short carbon cycle.

Demands for improved engine design and replacing the fossil fuel, in terms of power output, efficiency and emissions control, require improved fundamental understanding of the combustion processes that occur within the cylinder. The primary importance characteristic is the burning velocity, which directly affects pressure development and often is expressed in terms of laminar burning velocity. The laminar burning velocity is the most important flame propagation characteristic in spark ignition premixed combustion.

Simulation is the solution to solve the limitation of the complexity real experiment in the laboratory. The simulation can be visualize the preformance of the mechanical design in the real experiment during engineering design [1]. The simulation also can be visualize the preformance of the Combustion Process in the real experiment [13].

The unstretched laminar burning velocities of a freely propagating, one-dimensional, adiabatic premixed flame with the Sandia PREMIX code was computed for methane-air mixtures. This used a hybrid time-integration/ Newton-iteration technique to solve the steady state comprehensive mass, species, and energy conservation equations. Computations covered methane-air mixtures, Equivalence ratio ( $\phi$ )= 0.6 to 1.2, at initial temperatures and pressures between 300 and 400 K and 0.1 and 1.0 MPa. Sufficient grid points were allowed (usually 500) to ensure a converged solution [4].

The numerical simulation for methane-air mixtures at 298K initial temperature and atmospheric pressure (1 atm) initial condition for various equivalence ratio has been reported using CHEMKIN code based on a compilation of 325 elementary chemical reactions and associated rate coefficient expressions and thermochemical parameters for the 53 species involved in them. The flame speed against equivalent ratio result is shown in Fig. 1 [17].



**Figure 1.** Flame Speed Against Equivalent Ratio Methane-Air Mixtures

Based on the Fig. 1, there are a good (almost similar) result between all the report and the numerical simulation of flame speed in various equivalent ratio methane-air mixtures at initial conditions of a stoichiometric at room temperature and atmospheric pressure using CHEMKIN code based on a compilation of 325 elementary chemical reactions and associated rate coefficient expressions and thermochemical parameters for the 53 species involved in them.

## II. EXPERIMENTAL AND SIMULATION METHOD

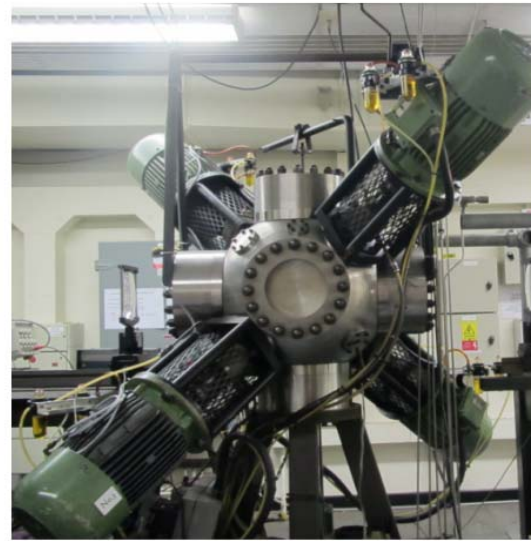
The experimental laminar burning velocity of biogas premixed combustion was measured in the Mk 2 high pressure fan-stirred bomb at the University of Leeds, England as shown in Fig. 2. The bomb is a spherical stainless steel vessel 380 mm diameter. The stainless steel bomb had three pairs of orthogonal windows of 150 mm diameter and was equipped with four fans driven by electric motors [3].

Based on the chemical composition analysis, the composition of biogas produced in East Java, Indonesia consists of 66.4% methane, 30.6% carbon dioxide and 3% nitrogen. Methane is a flammable gas, nitrogen is inert gases and carbon dioxide is an inhibitor gas [6,11].

**Table 1.** Composition of Biogas Produced in East Java

Matter	%
Methane	66.4
Carbon dioxide	30.6
Nitrogen	3.0

The experiments were conducted using Mk2 combustion bomb. The fuel-air mixtures have been centrally ignited and flame progress recorded by high speed schlieren cine-photography. The unstretched laminar burning velocity as the important characteristic of flame propagation in biogas premixed combustion have been found at stoichiometric, room temperature and atmospheric pressure initial conditions. The propagating flames were recorded by schlieren cine photography using a Photsonics Phantom digital camera, which ran at a framing rate of 2500 frames/s with a resolution of 768 x 768 in all the experiments. The flame radius was calculated as that of a circle encompassing the same area as that enclosed by the schlieren imaged flame. The laminar burning velocity is derived from schlieren photographs. Analysis based on careful photographic observation has been used to determine precisely defined (unstretched) laminar burning velocities. The biogas and air mixtures have been centrally ignited and flame progress recorded by high speed schlieren cine-photography. The images of the spherical flame propagating within the combustion vessel 150 mm windows and there are no significant rise in pressure occurred during the image recoding period [12].



**Figure 2.** Mk2 Combustion Bomb

The laminar burning velocity for a spherically expanding flame can be deduced from Schlieren, the stretched flame velocity ( $S_n$ ) can be derived from the flame radius versus time data as:  $S_n = dr/dt$ , where  $r$  is the flame radius in Schlieren photographs and  $t$  is the elapsed time from spark ignition. The flame stretch rate  $\alpha$  is defined as  $\alpha = d(\ln A)/dt = (dA)/(A dt)$ , where  $A$  is the area of the flame. In the case of spherically propagating premixed flame, the flame stretch rate can be calculated by  $\alpha = (2/r)(dr/dt)$  [2, 4, 9,10,12,13].

The linear relationship between flame speed and the total stretch exist, and this quantified by a burned gas 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 intercept value of  $S_n$  at  $\alpha = 0$ , in the plot of  $S_n$  against  $\alpha$ . The gradient of the best straight line fit to the experimental data gives  $L_b$ . The unstretched laminar burning velocity,  $u_l$ , is deduced from  $S_s$  using  $u_l = S_s (\rho_b / \rho_u)$ , where  $\rho_b$  is burned density of gas mixtures and  $\rho_u$  is unburned density of gas mixtures ) [2, 4].

The numerical simulation use the Premix module of CHEMKIN. The Premix module of CHEMKIN based on a compilation of 325 elementary chemical reactions and associated rate coefficient expressions and thermochemical parameters for the 53 species involved in them.

### III.RESULT AND DISCUSSION

The experiments were conducted using Mk2 combustion bomb. The stoichiometric biogas-air mixtures at initial room temperature and atmospheric pressure have been centrally ignited and flame propagation was recorded by high speed schlieren cine-photography.. The images result of the spherical flame propagating within the combustion vessel 150 mm windows are shown in Fig. 3.

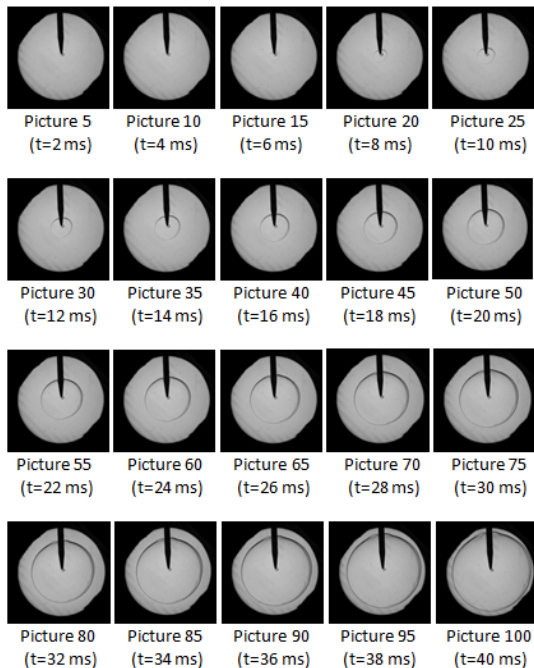


Figure 3. Flame Propagation Stoichiometric Biogas-Air Mixtures

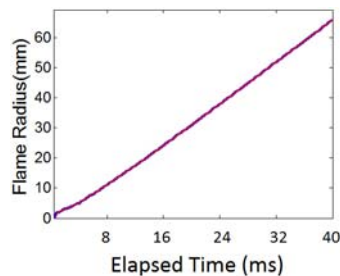


Figure 4. Flame Radius vs Elapsed Time of Flame Propagation Stoichiometric Biogas-Air Mixtures

The radius of spherical flame propagation in Fig. 3 are presented in Fig. 4 as a function of elapsed time. The stretched flame velocity ( $S_n$ ) can be derived from the flame radius at Fig. 4 as:  $S_n = dr/dt$ , where  $r$  is the flame radius in Schlieren photographs and  $t$  is the elapsed time from spark ignition. The flame stretch rate  $\alpha$  is defined as  $\alpha = d(\ln A) / dt = (dA) / (A dt)$ , where  $A$  is the area of the flame. In the case of spherically propagating premixed flame, the flame stretch rate can be calculated by  $\alpha = (2/r)(dr/dt)$ . A linear relationship between flame speed and the total stretch exist, and this quantified by a burned gas 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 intercept value of  $S_n$  at  $\alpha = 0$ , in the plot of  $S_n$  against  $\alpha$ . The gradient of the best straight line fit to the experimental data gives  $L_b$ . The unstretched laminar burning velocity,  $u_l$ , is deduced from  $S_s$  using  $u_l = S_s (\rho_b / \rho_u)$ , where  $\rho_b$  is burned density of gas mixtures and  $\rho_u$  is unburned density of gas mixtures. Based on the experimental result, the laminar burning velocity of biogas premixed combustion has been found for initial conditions of a stoichiometric at room temperature and atmospheric pressure is 0.2638 m/s.

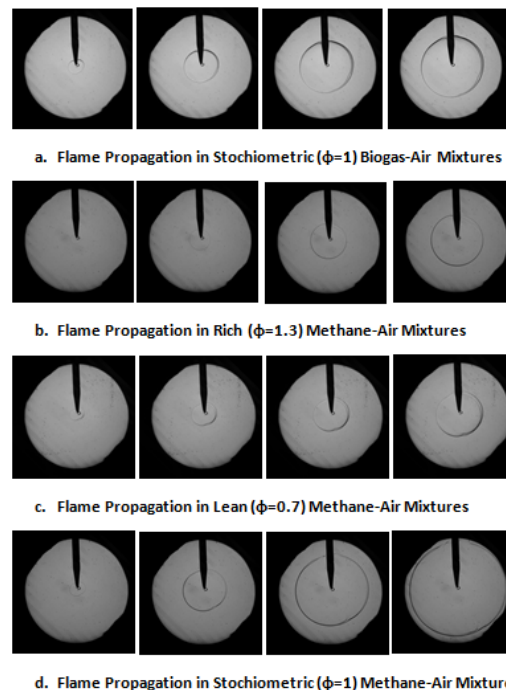


Figure 5. The Real Experimental Result Comparison for Four Fuel-Air Mixtures

The flame propagation at the same time comparison flame propagation of four fuel-air mixtures is shown in Fig. 5. The fuel-air mixtures are stoichiometric (equivalence ratio ( $\phi$ )=1) biogas-air mixtures, rich ( $\phi$ =1.3) methane-air mixtures, lean ( $\phi$ =0.7) methane-air mixtures, stoichiometric ( $\phi$ =1) methane-air mixtures. The flame propagation measured at room temperature and atmospheric pressure initial conditions. The flame propagation of stoichiometric biogas-air mixtures is faster than flame propagation of rich and lean methane-air

mixtures. The flame propagation of stoichiometric biogas-air mixtures is lower than flame propagation of stoichiometric methane-air mixtures (Fig. 5).

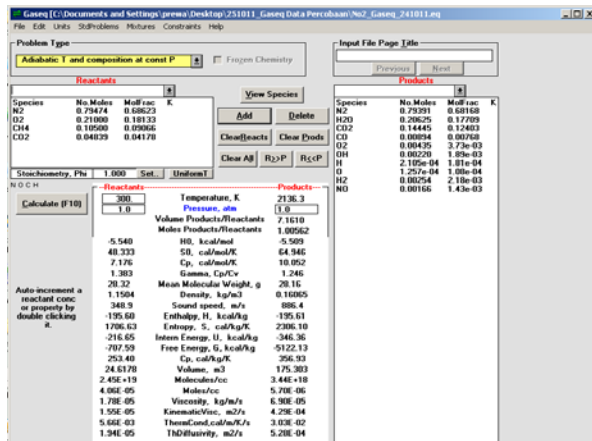


Figure 6. Properties of Stoichiometric Biogas-Air Mixtures

The properties of stoichiometric (equivalence ratio ( $\phi$ )=1) biogas-air mixtures at room temperature and atmospheric pressure initial condition is shown in Fig 6. Based on the Gaseq software, the properties are unburned density, burned density, unburned kinetic viscosity and burned kinetic viscosity are  $1.1504 \text{ kgm}^{-3}$ ,  $0.16065 \text{ kgm}^{-3}$ ,  $1.55\text{E-}05 \text{ m}^2\text{s}^{-1}$ , and  $4.29\text{E-}04 \text{ m}^2\text{s}^{-1}$ .

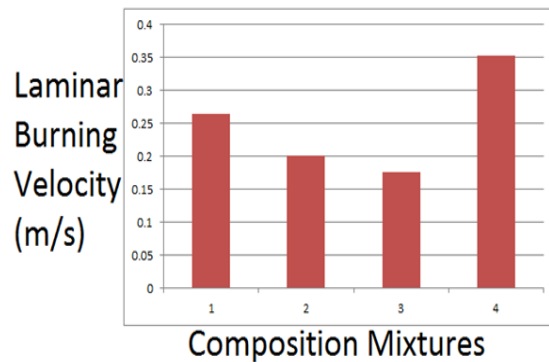
Table 2. Experimental and Numerical Simulation Results of Stoichiometric Biogas-Air Mixtures at room temperature and atmospheric pressure initial conditions

	Experimental Results	Numerical Simulation Results
Flame speed (m/s)	1.89	1.97
Laminar burning velocity (m/s)	0.2638	0.2746

The laminar burning velocity as the important characteristic of flame propagation in the fuel-air mixtures premixed combustion have been found as Table 2. Both experimental and numerical simulation give the same agreement (have similar values). The numerical simulation laminar burning velocity error is 4.09% respected to the experimental result.

Table 3. Stoichiometric Biogas-Air, Rich Methane-Air, Lean Methane-Air, and Stoichiometric Methane-Air Mixtures Comparison Results

	Stoichiometric ( $\phi=1.0$ ) Biogas-Air Mixtures	Rich ( $\phi=1.3$ ) Methane-Air Mixtures	Lean ( $\phi=0.7$ ) Methane-Air Mixtures	Stoichiometric ( $\phi=1.0$ ) Methane-Air Mixtures
Unburned density ( $\text{kg/m}^3$ )	1.1504	1.10950	1.13640	1.1226
Burned density ( $\text{kg/m}^3$ )	0.16065	0.15323	0.18542	0.15017
Unburned kinematic viscosity ( $\text{m}^2/\text{s}$ )	1.55E-05	1.61E-05	1.60E-05	1.60E-05
Burned kinematic viscosity ( $\text{m}^2/\text{s}$ )	4.29E-04	4.36E-04	3.38E-04	4.72E-04
Flame speed (m/s)	1.89	1.46	1.08	2.64
Laminar burning velocity (m/s)	0.2638	0.2015	0.1762	0.3527



- Composition Mixtures 1: Stoichiometric ( $\phi=1.0$ ) Biogas-Air Mixtures
- Composition Mixtures 2: Rich ( $\phi=1.3$ ) Methane-Air Mixtures
- Composition Mixtures 3: Lean ( $\phi=0.7$ ) Methane-Air Mixtures
- Composition Mixtures 4: Stoichiometric ( $\phi=1.0$ ) Methane-Air Mixtures

Figure 6. Laminar Burning Velocity Comparison Results of Stoichiometric Biogas-Air, Rich Methane-Air, Lean Methane-Air, and Stoichiometric Methane-Air Mixtures

Table 3 and Fig. 6 show the premixed combustion flame propagation characteristic of stoichiometric biogas-air mixtures, stoichiometric methane-air mixtures, lean ( $\phi=0.7$ ) methane-air mixtures and rich ( $\phi=1.3$ ) methane-air mixtures. The laminar burning velocity of stoichiometric biogas is higher than methane-air mixtures at lean ( $\phi=0.7$ ) and rich ( $\phi=1.3$ ) at room temperature and atmospheric pressure initial condition. The laminar burning velocity of stoichiometric biogas is lower than stoichiometric methane-air mixtures at room temperature and atmospheric pressure initial condition because of the chemical composition of biogas. Biogas consists of 66.4% methane, 30.6% carbon dioxide and 3% nitrogen. Methane is a flammable gas. Carbon dioxide and nitrogen are impurities as inhibitor gases.

#### IV. CONCLUSIONS

Numerical simulation can be visualize the preformance of the combustion process in the real experiment. The numerical simulation use the Premix module of CHEMKIN. The Premix module of CHEMKIN based on a compilation of 325 elementary chemical reactions and associated rate coefficient expressions and thermochemical parameters for the 53 species involved in them. There are a good agreement (have similar values) between experimental and numerical simulation results of laminar burning velocity of biogas-air mixtures. The numerical simulation laminar burning velocity error is 4.09% respected to the experimental result.

Based on the experimental investigation and the numerical simulation, the unstretched laminar burning velocity as the important characteristic of flame propagation in biogas premixed combustion has been found for initial conditions of a stoichiometric at room temperature and atmospheric pressure. Finally, The laminar burning velocity of biogas is higher than pure methane in lean ( $\phi=0.7$ ) and rich ( $\phi=1.3$ ) mixtures at room temperature and atmospheric pressure initial



conditions. Biogas has a good premixed combustion flame propagation characteristic and could be an alternative to replace the fossil fuels. Biogas is one of the solution for green technology for sustainable development of the combustion processes.

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