BIOGAS COMBUSTION CHARACTERISTICS UNDER VARYING CARBON DIOXIDE DILUTION AND HYDROGEN ENRICHMENT

MOHD SUARDI SUHAIMI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Chemical Engineering)

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

FEBRUARY 2020

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my supervisors, Dr. Aminuddin Saat, for endless support, encouragement, guidance and critics. I am also very thankful to my co-supervisors Professor Dr. Mazlan Abd. Wahid and Dr. Mahadhir Mohamed for their guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here. I am also indebted to Universiti Teknologi Malaysia (UTM) for funding my study.

My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. Above all, I dedicate this thesis to my wife and kids for their endless support and sacrifices.

ABSTRACT

This study investigates the combustion characteristics of four different types of gaseous fuels namely methane (CH_4), biogas, simulated biogas with varying carbon dioxide (CO_2) content and hydrogen enriched biogas under atmospheric condition. Flammability, laminar burning velocity and flame stability of each fuel are among the combustion characteristics investigated using spherical flame method. Measurement of these parameters is important to explain the effects of CO_2 and hydrogen on biogas combustion which are still lacking in literature. CH_4 flammability range was found to be within the equivalence ratio of 0.7 to 1.3 with peak laminar burning velocity at approximately 36 cm/s which agrees well with previous findings. For biogas, flammability range narrows to equivalence ratio range of 0.6 to 0.9 with a peak laminar burning velocity of around 24 cm/s. For simulated biogas, as CO_2 content increased, the flammability range tended to become narrower with appreciable decrease in laminar burning velocity. Peak laminar burning velocity value steadily decreased to 21%, 34% and 45% as CO_2 content was increased from 20% to 40% and 50% respectively. CO_2 could slow down the reactions that produce radicals important for CH_4 dissociation. It could also modify mass and thermal diffusion pattern as indicated by the corresponding changes in Markstein length. For hydrogen enriched biogas, the flammability limits widened to the leaner side from equivalence ratio of 0.4 to 0.9 for 30% and 40% enrichment. Both flame speed and laminar burning velocity were enhanced with hydrogen enrichment especially at 30% and 40% which led to significant increase in maximum laminar burning velocity to 52 % and 88 % respectively. Flame appeared to become less stable under leaner conditions as supported by the occurrence of buoyancy and mild cellularity at the equivalence ratio of 0.4 and 0.5 under 30% and 40% hydrogen enrichment. Simulation revealed dramatic increase in H radical at 30% hydrogen enrichment onwards. These observations imply the significance of hydrogen on biogas combustion both on laminar burning velocity and flame stability.

ABSTRAK

Kajian ini bertujuan menyelidik sifat-sifat pembakaran bagi empat jenis bahanapi gas iaitu metana (CH_4), biogas, biogas tersimulasi dengan variasi kandungan karbon dioksida (CO_2) dan biogas yang diperkaya dengan hidrogen di bawah keadaan atmosfera. Kebolehbakaran, halaju pembakaran laminar dan kestabilan nyala adalah antara sifat-sifat pembakaran yang dikaji menggunakan kaedah nyala sfera. Pengukuran parameter-parameter ini adalah penting bagi menjelaskan kesan-kesan CO_2 dan hidrogen terhadap pembakaran biogas yang mana masih kurang dilaporkan. Julat kebolehbakaran CH_4 ialah diantara nisbah kesetaraan 0.7 hingga 1.3 dengan puncak halaju pembakaran laminar kira-kira 36 cm/s yang mana menyamai hasil kajian terdahulu. Bagi biogas, julat kebolehbakaran mengecil antara nisbah kesetaraan 0.6 hingga 0.9 dengan nilai puncak halaju pembakaran laminar pada kira-kira 24 cm/s. Bagi biogas tersimulasi pula apabila kandungan CO_2 meningkat, julat kebolehbakaran didapati mengecil dengan halaju pembakaran laminar menurun. Nilai puncak halaju pembakaran laminar berkurang sebanyak 21%, 34% dan 45% apabila kandungan CO_2 bertambah masing-masing dari 20% kepada 40% dan 50%. CO_2 berupaya memperlahankan tindakbalas-tindakbalas yang menghasilkan radikal-radikal penting dalam penguraian CH_4. Ia juga berupaya mengubah corak penyebaran haba dan jisim seperti ditunjukkan oleh perubahan dalam kepanjangan Markstein. Bagi biogas yang diperkaya hidrogen, julat kebolehbakaran bagi kandungan hidrogen 30% dan 40% didapati melebar dari nisbah kesetaraan 0.4 hingga 0.9. Kedua-dua laju nyala dan halaju pembakaran laminar telah ditingkatkan dengan pengayaan hidrogen khususnya pada 30% dan 40% yang mana telah meningkatkan halaju pembakaran laminar maksimum secara ketara masing-masing kepada 52% dan 88%. Nyala kelihatan kurang stabil dibawah keadaan yang lebih langsing disokong dengan nyalaan apungan dan selulariti sederhana pada nisbah kesetaraan 0.4 dan 0.5 di bawah pengayaan hidrogen 30% dan 40%. Simulasi mendedahkan peningkatan radikal H yang dramatik bermula dari kandungan hidrogen 30%. Ini menunjukkan pengaruh hidrogen yang amat ketara dalam pembakaran biogas dari segi halaju dan juga kestabilan nyala.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BG50	Biogas with 50% methane
BG60	Biogas with 60% methane
BG80	Biogas with 80% methane
BOD	Biochemical oxygen demand
BTE	Brake thermal efficiency
CH_4	Methane
CJ	Chapman Jouget
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical oxygen demand
CPO	Crude palm oil
CVCC	Constant volume combustion chamber
DRM	Developed Reduced Mechanism
GHG	Green house gasses
GRI	Gas Research Institute
ICE	Internal combustion engine
H_2	Hydrogen
LPG	Liquefied petroleum gas
NOx	Nitrogen oxides
NUIG	National University of Ireland Galway
PAH	Polycyclic Aromatic Hydrocarbon
POME	Palm oil mill effluent
SI	Spark ignition
STP	Standard temperature and pressure
TCD	Thermal conductivity detector
UTM	Universiti Teknologi Malaysia

LIST OF SYMBOLS

α	Flame stretch
A	Pre-exponenial Factor
A_f	Spherical Flame Surface Area
a_{tt}	Tangential Strain Rate
β	Secondary Temperature Dependency
C	Capacitance
χ	Hydrogen enrichment percentage
$\Delta_r H^{\circ}$	Enthalpy of combustion
E	Energy
$E_{l,min}$	Minimum ignition energy
d_q	Quenching distance
δ_l	Laminar flame thickness
δ_D	Flame thickness
D_u	Mass diffusivity
f	Mass flux
Ka	Karlovitz Number
k	Rate Constant
λ_v	Air/Fuel Ratio
λ	Thermal conductivity
m_{LZ}	Mass of Air
m_B	Maximum Convertible Fuel Mass
L_b	Markstein Length
Le	Lewis Number
L_{min}	Fuel Specific Stoichiometric Air Requirement
$(A/F)_{stoic}$	Stoichiometric Air-Fuel Ratio
M	Mach Number
Ma	Markstein Number
MW_{air}	Molecular Weight of Air
MW_{fuel}	Molecular Weight of Fuel
ρ_b	Burned Gas Density

ρ_u	Unburned Gas Density
ϕ	Equivalence Ratio
R	Universal Gas Constant
R^2	Coefficient of Determination
Re_c	Critical Reynolds Number
R_f	Flame Radius
$R_{f,c}$	Critical Radius at the Onset of Cellularity
γ	Specific Heat Ratio
σ	Density ratio
S_n	Stretched Flame Speed
S_s	Unstretched Flame Speed
u_L	Laminar Burning Velocity

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Depleting supply and stricter emission regulation has motivated the search for alternative fuels that are both green and sustainable to meet the increasing global demand for energy and emission regulation (Basha *et al.*, 2009; Hosseini and Wahid, 2013). Fossil fuel is still the main energy source for transportation, industrial and agricultural activities. Based on current consumption trend, it is projected that fossil fuel will become fully exhausted by 2050 (Basha *et al.*, 2009).

Biogas could be one of the potential alternative fuels to cater future energy demand. It is a product of anaerobic fermentation of various wastes could be the energy of the future. It is mainly consists of around 50-70% methane and 30-50% carbon dioxide with several other trace gases at smaller quantity. Abundant supply could be the main factor that could turn biogas as the promising fuel that could meet future energy demand. Biogas could be the potential fuel especially in the power plant to meet the ever increasing demand for energy. It has drawn the attention of researchers to the extent that many studies have been conducted to assess the potential of biogas to fuel both stationary and non-stationary engines (Razbani *et al.*, 2011). The use of biogas can also help in reducing Green House Gas (GHG) emission as biogas combustion produces lesser pollutants than fossil fuels (Schoen and Bagley, 2012).

At present, Germany is the global leader in biogas utilization with almost 600% growth in power generation from 60 kW_e in 1999 to 350 kW_e in 2008 (Poeschl *et al.*, 2010). Biogas utilization by means of combustion is mainly for generating electricity, powering vehicle, domestic use etc. (Poeschl *et al.*, 2010; Soleimani, 2010). Biogas has a big potential to be used in any type of engine provided the correct technique on its utilization is observed.

Combustion is one way to extract the energy contained within the chemical bonds of the fuel molecules. During combustion, fuel molecules are oxidized via a chemical reaction with oxygen releasing heat and forming certain combustion products (Moran and Shapiro, 2004). However, knowledge on the combustion characteristics of biogas is necessary to optimize the use of biogas while at the same time reducing the unwanted combustion by-products (Metgalchi and Keck, 1980). The interaction between its major components i.e. CH_4 and CO_2 could lead to unpredictable combustion characteristics that could hinder the commercial use of biogas (Fischer and Jiang, 2015). Thus, it is imperative to study biogas combustion characteristics at its fundamental level. Knowledge about its combustion characteristics could also be useful in the design of practical combustors that can efficiently run on biogas (Diaz-Gonzalez at al., 2009).

This study focuses on the laminar fully premixed biogas combustion. This kind of combustion permits the burning of the fuel at equivalence ratio other than the stoichiometric. Thus lower temperature combustion can be achieved under the lean condition. Laminar burning velocity, flammability limit, flame stability and Markstein length are among the properties widely used to describe the combustion behavior of certain fuel. These properties are unique for every different fuel as they are directly influenced by fuel properties to a certain extent.

It was well reported that the presence of CO_2 can significantly affect the combustion characteristics of biogas in certain way. CO_2 can act as a diluent absorbing some of the heat generated during combustion. This implies that the flame propagation, flammability limits and flame stability are all affected by the presence of CO_2 (Hinton and Stone, 2014). In addition, CO_2 can also promote flame buoyancy as it dilutes the concentration of the only flammable component of biogas which is methane per given biogas volume.

Laminar burning velocity is the velocity at which the combustible mixture propagates into the reaction zone. It directly influence the development of pressure especially within a closed system. It is also the most important flame property in spark ignited premixed combustion such as those found in automobiles’ gasoline engine. The presence of CO_2 has been found to affect the laminar flame velocity of biogas where an increase in CO_2 concentration would cause a corresponding decrease in the laminar flame velocity. This reduction could become more apparent in richer fuel and oxidizer mixture.

Flammability limits which consist of the lower and upper limits define the range within which the fuel and oxidizer mixture is flammable. The lower and upper flammability limit are the leanest and richest mixture at which the fuel could combust with sustained flame respectively. If the lower flammability limit of biogas is lower than current gas such as natural or liquefied petroleum gas (LPG), biogas could combust with a much smaller volume compared to these gasses improving fuel economy. In fact, recent study by Anggono et al. (2014) reveals that the flammability limit of biogas depends on the initial pressure at which the biogas start to combust.

Markstein length is a parameter that describes the effects of changes in flame structure due to stretching to the flame speed (Moccia and D'Alesio, 2013). It is influenced by the chemical and transport properties of the reacting mixtures. It is important to evaluate this quantity as it could serve as an indicator whether the flame extinction could occur for a particular combustible fuel and oxidizer mixture.

Buoyancy is known to alter flame configuration distorting its structure and making analysis difficult. It is likely to occur for a lean mixture. The net convective motion resulting from buoyancy could affect combustion in certain way; it may hamper flame propagation and to some extent cause the flame to propagate back into the burnt region. Once this happens, flame will extinguish due to the low fuel and oxidizer concentration in that region.

As reported in literature, an increase in CO_2 concentration and reduces combustible mixture concentration approaching its lower flammability limit. In other words, the mixture becomes leaner in the presence of CO_2. This could lead to various form of instabilities and to some extent flame extinction.

Extinction would occur if there are stretching, nonequidiffusion (for the case where thermal diffusivity is higher than mass diffusivity) and incomplete reaction (for the case where mass diffusivity is higher than thermal diffusivity). The presence of CO_2 may contribute to flame extinction as it could absorb some of the heat generated during combustion.

1.2 Problem Statement

Palm Oil Mill Effluent (POME) is a type of effluent generated by palm oil processing. POME is usually channeled into treatment ponds where biogas is emitted during the treatment process. This gas could serve as an alternative energy as it contains significant amount of methane that could be harnessed to generate power especially in the form of electricity. As the second largest oil palm exporter, Malaysia should tap into this renewable resource in an attempt to implement sustainable energy generation that are both economical and environment friendly.

The benefits of tapping biogas are plentiful. First, it could reduce methane and CO_2 that would otherwise be released to the environment contributing to global warming. Anaerobic digester used in biogas capture instead of aerobic pond for POME treatment will minimize land area required for effluent treatment. Extra revenue can also be gained from palm oil milling process as it can also supply fuel.

However, the feasibility of using biogas as a fuel of power plant generator still remains subtle. The manner the combustion of biogas affects both the combustor in power plant generator and amount energy generated is of paramount importance. This would require a thorough study on biogas combustion characteristics.

The content of CO_2 may adversely affect biogas combustion as it would reduce calorific value, laminar burning velocity, flame speed and stability (Lee and Hwang, 2007). It was established in the literature that CO_2 may physically and chemically affect biogas combustion to a certain degree depending on its content. Physically, it could absorb some of the heat from combustion, reducing the temperature and also the flame speed. Chemically, it could reduce the formation of certain radicals important during ignition and subsequently the propagation of flame. There are also limited experimental studies in literature to elucidate such effects and data on are still scarce as there are limited experimental studies reported in literature (Zeng et al, 2018). Laminar burning velocity measurement is important to elucidate effects of CO_2 on biogas combustion. Numerical studies by Fischer and Jiang (2015) shows that CO_2 could significantly reduce biogas reactivity especially under higher CO_2 content (50%). This is supported by a substantial decrease in CO mass fraction that would affect certain reactions that are important to combustion. Therefore, a subsequent decrease in biogas laminar burning velocity is expected with an increase in CO_2 content. This would render the direct use of biogas is limited to certain types of combustors that can effectively accommodate biogas distinct and inferior combustion characteristics.

Introduction of certain additives to biogas may to some extent improve biogas combustion characteristics. Hydrogen is among the additives that has attracted the attention of researchers over the recent years. Due to its wider flammability and relatively high mass diffusivity compared to CH_4 and CO_2, hydrogen could improve biogas combustion especially in terms of flammability and laminar burning velocity. Studies on the combustion characteristics of hydrogen enriched biogas are still scarce in literature (Hu and Zhang, 2019). Cardona and Amell (2013) reported that the addition of hydrogen could enhance biogas laminar burning velocity. In terms of stability, the addition of hydrogen as additive has effectively widen the range within which the flame is stable (Leung and Wierzba, 2008). A recent study also reported an increase in flame stability via a small addition of hydrogen in biogas (Zhen et al., 2014). However this study only investigate biogas combustion under stoichiometric and rich due to the flammability limits of biogas. Biogas could only be ignited at φ of 0.9 with and addition of 10% (v/v) hydrogen. Extending the lean limit of biogas combustion could be both economically and environmentally favorable as less biogas would be burn and consequently producing less pollutants.

Understanding the possible combustion chemistry resulted from the use of hydrogen as an additive at certain percentage still remains as one of the most challenging task. To achieve this, it is imperative to study the effect of hydrogen on combustion characteristics such as flame propagation, flame stability and flammability limits. Quantitatively, this can be achieved by solving the governing equations together with detailed chemistry. This study therefore aimed at gaining insight of the underlying chemistry and physics involved that affect biogas combustion.

1.3 Research Objectives and Scopes

The objectives and scopes of this study could be summarized as:

I. To investigate the combustion characteristics of simulated biogas with varying CO_2 content within equivalence ratio range of 0.6 to 1.1.
II. To evaluate the combustion characteristics of actual biogas from POME with and without hydrogen as an additive within equivalence ratio range of 0.5 to 0.9.
III. To modify reaction mechanisms of simulated and actual biogas combustion in the presence of hydrogen.

This study will only cover low quality biogas as it is the least studied biogas in literature. This study covers the study of combustion characteristics such as flammability limits, flame speed, laminar burning velocity, stretch rate, Markstein length and heat release rate of pure methane, biogas and biogas with hydrogen as additive. Percentage of CO2 and hydrogen was varied to investigate the effect of their variation on combustion characteristics. Pure methane combustion serves as the control experiment.

1.4 Significance of Study

Biogas could be considered as an untapped energy resource especially in Malaysia where much of the energy generated come from fossil fuel combustion. The use of biogas may reduce the country's dependence on the depleting fossil fuel that is has also saw dwindling price due to shortage in supply. Since biogas contains significant amount of CO_2, it may also cause GHG emission problem if left untapped. The presence of CO_2 may also give biogas distinct combustion characteristics that are not always favorable. There are numerous data on laminar burning velocity of biogas both numerically and experimentally. Nonetheless, data on low quality biogas; biogas with 50% of CO_2 or larger by volume are still scarce. Although biogas generation has been utilized since the 1950's, and the principles of digestion are well documented, little is known about the burning of such gases. Most works in literature involve numerical simulation, with relatively fewer experimental data.

It is important to improve these shortcomings prior to the effective use of biogas as a fuel. This however, requires the understanding of the physics and chemistry involved during the combustion. Addition of hydrogen has been shown to favorably improve biogas combustion, but little is known about how hydrogen alters the chemistry and physics of biogas combustion. Observations that will be made through this study will hopefully contribute to the existing knowledge. This would provide an invaluable insight especially for the execution of further studies. The study of laminar premixed combustion of biogas may also serve as building blocks for turbulent combustion understanding. This could significantly help in the design of many practical combustors that mostly employ turbulent combustion.

Addition of hydrogen has been shown to favorably improve biogas combustion, but little is known about how hydrogen alters the chemistry and physics of biogas combustion (Hu and Zhang, 2019). Simulation with ANSYS Chemkin will help to determine important chemical reactions that affect biogas combustion. It would also allow the determination and modification of the rates of such reactions. Schlieren photography is a versatile and sophisticated technique that captures flame images due to density gradient. This implies that, even the slightest change in density resulting from combustion could be captured clearly as flame image and will help flame speed and stability analysis.

REFERENCES

Agrawal, D. D. (1981) ‘Experimental determination of burning velocity of methane-air mixtures in a constant volume vessel’, *Combustion and Flame,* 42, pp. 243-52.

Ahmad, A. L., Ismail, S., and Bhatia S. (2003) ‘Water recycling from palm oil mill effluent (POME) using membrane technology’, *Desalination*; 157, pp. 87-95.

Andrews, G. E., and Bradley D. (1972) ‘The burning velocity of methane-air mixtures’, *Combustion and Flame,* 19**,** pp. 275-88.

Anggono, W., Wardana, I. N. G., Lawes, M., and Hughes, K. J. (2014) ‘Effect of Inhibitors on Biogas Laminar Burning Velocity and Flammability Limits in Spark Ignited Premix Combustion’, *International Journal of Engineering and Technology (IJET),* 5(6), pp. 4980-4987.

Aung, K. T., Hassan, M. I., and Faeth G. M. (1997) ‘Flame stretch interaction of laminar premixed hydrogen/air flames at normal temperature and pressure’, *Combustion and Flame* 109, pp. 1-24.

Aung, K.T, Hassan, M.I, and Faeth G.M. (1998) ‘Effects of pressure and and nitrogen dilution on flame/stretch interactions of laminar premixed H_2/O_2/N_2 flames’, *Combustion and Flame*, 112(1–2), pp. 1-15.

Bari, S. (1996). ‘Effect of carbon dioxide on the performance of biogas/diesel duel-fuel engine’ *Renewable Energy*, 9(1), pp. 1007-1010.

Borden, W.T, Hoffmann, R., Stuyver, T., Chen, B. (2017). ‘Dioxygen: What Makes This Triplet Diradical Kinetically Persistent?’. *Journal of the American Chemical Society*. 139(26), pp. 9010–9018.

Bosschaart, K. J., and de Goey, L. P. H. (2004) ‘The laminar burning velocity of flames propagating in mixtures of hydrocarbons and air measured with the heat flux method’ *Combustion and Flame,* 136, pp. 261–269.

Boushaki, T., Dhue, Y., Selle, L., Ferret, B., and Poinsot, T. (2012) ‘Effects of hydrogen and steam addition onlaminar burning velocity of methane-air premixed flame: experimental and numerical analysis’, *International Journal of Hydrogen Energy*, 37, pp. 9412-22.

Bouvet N, Halter F, Chauveau C, and Yoon Y. (2013) ‘On the effective Lewis number formulations for lean hydrogen/hydrocarbon/air mixtures’, *International journal of hydrogen energy*, 38(14), pp. 5949-5960.

Bradley, D., Lung, and K. K. (1987) ‘Spark Ignition and the Early Stages of Turbulent Flame Propagation’, *Combustion and Flame*, 69, pp. 71-93.

Bradley, D., Gaskell, P. H., and Gu, X. J. (1996) ‘Burning velocities, Markstein lengths, and flame quenching for spherical methane-air flames: A computational study’, *Combustion and Flame*, 104, pp. 176–198.

Bradley, D., Hicks, R. A., Lawes, M., Sheppard, C. G. W., and Woolley, R. (1998) ‘The Measurement of Laminar Burning Velocities and Markstein Numbers for Iso-octane–Air and Iso-octane–nHeptane–Air Mixtures at Elevated Temperatures and Pressures in an Explosion Bomb’, *Combustion and Flame*, 115(1-2), pp.126-144.

Cardona, C., and Amell, A. A. (2013) ‘Laminar burning velocity and interchangeability analysis of biogas/C_3H_3/H_2 with normal and oxygen-enriched air’, *International Journal of Hydrogen Energy*,39, pp. 7994-8001.

Cengel, Y.A. (2003) Heat Transfer: A Practical Approach. McGraw Hill.

Chao, B. H., Egolfopoulos, F. N., and Law, C. K. (1997) ‘Structure and propagation of premixed flame in nozzle-generated counterflow’, *Combustion and Flame*, 109, pp. 620–638.

Chen, Z. (2010) ‘Effects of radiation and compression on propagating spherical flames of methane/air mixtures near the lean flammability limit’, *Combustion and flame*, 157, pp. 2267-2276.

Choorit, W., and Wisarnwan, P. (2007) ‘Effect of temperature on the anaerobic digestion of palm oil mill effluent’ *Electronic Journal of Biotechnology*, 10, pp. 376-85.

Clarke, A. (2002) ‘Calculation and consideration of the Lewis number for explosion studies’, *Trans IChemE*; 80, pp. 135-140.

Clingman, W. H., Brokaw, R. S., and Pease, R. N. (1952) ‘Burning velocities of methane with nitrogen-oxygen, argon-oxygen and helium-oxygen mixtures’, *Proc. Combust. Inst.*, 4, pp. 310-13.

Dowdy, R. D., Smith, D. B., Taylor, S. C., and Williams, A. (1990) ‘The use of expanding spherical flames to determine burning velocities and stretch effects in hydrogen/air mixtures’, *Proc. Combust. Inst.*, 23, pp. 325-32.

Dinkelacker, F., Manickam, B., and Muppala, S. P. R. (2011) ‘Modelling and simulation of lean premixed turbulent methane/hydrogen/air flames with an effective Lewis number approach’, *Combustion and Flame*; 158, pp. 1742-1749.

Edmondson, H., and Heap, M. P. (1969) ‘The burning velocity of methane-air flames inhibited by methyl bromide’, *Combustion and Flame*, 13, pp. 472-78

Edmondson, H., and Heap, M. P. (1970) ‘Ambient atmosphere effects in flat-flame measurements of burning velocity’, *Combustion and Flame*, 14, pp. 195-202.

Egolfopoulos, F. N., Zhu, D. L., and Law, C. K. (1990) ‘Experimental and numerical determination of laminar flame speeds: mixtures of C2-hydrocarbons with oxygen and nitrogen’, *Proc. Combust. Inst.*, 23, pp. 471-478.

Elia, M., Ulinski, M., and Metghalchi, M. (2001) ‘Laminar burning velocity of methane–air–diluent mixtures’, *Trans. ASME*, 123, pp. 190-196.

Fischer M., and Jiang X. (2015) ‘An Investigation of the Chemical Kinetics of Biogas Combustion’, *Fuel*, 150, pp. 711-720.

Gillespie, L., Lawes, M., Sheppard, C. G. W., and Woolley, R. (2000) ‘Aspects of Laminar and Turbulent Burning Velocity Relevant to SI Engines’, *Society of Automotive Engineers*, 109(3), pp. 13-33.

Groff, E. D. (1982). The cellular nature of confined spherical propane-air flames *Combustion and Flame*, 48**,** pp. 51-62.

Gu, X. J., Haq, M. Z., Lawes, M., and Woolley,R. (2000) ‘Laminar burning velocity and Markstein lengths of methane–air mixtures’, *Combustion and Flame*, 121, pp. 41–58.

Han W., and Chen Z. (2015) ‘Effects of Soret diffusion on spherical flame initiation and propagation’, *International Journal of Heat and Mass Transfer*, 82, pp. 309–315.

Hassan, M. I., Aung, K. T., and Faeth, G. M. (1998) ’Measured and predicted properties of laminar premixed methane/air flames at various pressures’ *Combustion and Flame*, 115, pp. 539–550.

Hinton, N., and Stone, R. (2014) ‘Laminar Burning Velocity Measurements of Methane and Carbon Dioxide Mixtures (Biogas) Over Wide Ranging Temperatures and Pressures’ *Fuel*, 116, pp. 743-750.

Hirschfelder, J.O., Curtiss, C.F., and Bird, R.B. (1954). Molecular Theory of Gases and Liquids. John Wiley.

Hu, J., Zhang, L., Liang, W. and Wang, Z. (2009) ‘Incipient mechanical fault detection based on multifractal and MTS methods’, *Petroleum Science,* 6(2), pp. 208–216.

Hu, Z., and Zhang, X. (2019) ‘Experimental study on flame stability of biogas / hydrogen combustion’, *International Journal of Hydrogen Energy*, 44(11), pp. 5607-5614.

Hu, Z., and Zhang, X. (2019) ‘Study on laminar combustion characteristic of low calorific value gas blended with hydrogen in a constant volume combustion bomb’, *International Journal of Hydrogen Energy*, 44, pp. 487-493.

Huang, Z., Zhang, Y, Zeng, K., Liu, B., Wang, Q., and Jiang, D. (2006) ‘Measurements of laminar burning velocities for natural gas-hydrogen-air mixtures’, *Combustion and Flame*, 146, pp. 302-311.

Iijima, T., and Takeno, T. (1986) ‘Effects of temperature and pressure on burning velocity’, *Combustion and Flame*, 65, pp. 35-43.

Ilbas, M., Crayford, A. P, Yılmaz, I., Bowen, P. J., and Syred, N. (2006) ‘Laminar-burning velocities of hydrogen-air and hydrogen-methane-air mixtures: an experimental study’, *Int. J. Hydrogen Energy*, 31**,** pp. 1768-79.

Jackson, G. S., Sai, R., Plaia, J. M., Boggs, C. M., and Kiger, K. T. (2003) ‘Influence of H_2 on the response of lean premixed CH_4 flames to high strained flows’, *Combustion and Flame*, 132, pp. 503–511.

Karim G.A., Wierzba I., and Al-Alousi Y. (1996) ‘Methane–hydrogen mixtures as fuels’, *International Journal of Hydrogen Energy*, 21(7), pp. 625–631.

Konnov, A. A., Dyakov, I. V., and De Ruyck, J. (2003) ‘Measurement of adiabatic burning velocity in ethane–oxygen–nitrogen and in ethane–oxygen–argon mixtures’, *Exp. Therm. Fluid Sci*., 27, pp. 379–384.

Kwon, O. C., and Faeth, G. M. (2001) ‘Flame/stretch interactions of premixed hydrogen-fueled flames: measurement and predictions’, *Combustion and Flames*, 124, pp. 590-610.

Lafay, Y., Taupin, B., Martins, G., Cabot, G., Renou, B., and Boukhalfa, A. (2007) ‘Experimental studies of biogas combustion using a gas turbine configuration’, *Experiments in Fluids*, 43(2), pp. 395-410.

Lamoureux, N., Djebaili-Chaumeix, N., and Paillard, C. E. (2003) ‘Laminar flame velocity determination for H_2−air−He−CO_2 mixtures using the spherical bomb method’, *Exp. Therm. Fluid, Sci.*, 27, pp. 385-93.

Law, C. K., and Kwon O. C. (2004) ‘Effects of hydrocarbon substitution on atmospheric hydrogen-air flame propagation’, *International Journal of Hydrogen Energy*, 29, pp. 876-879.

Law, C.K. (2006). *Combustion Physics*. Cambridge University Press.

Lee, H. C., Mohamad, A. A., and Jiang, L. Y. (2015) ‘Comprehensive comparison of chemical kinetics mechanisms for syngas/biogas mixtures’ *Energy & Fuel*, 29(9), pp. 6126–6145.

Liang, W., Chen, Z., Yan, F., and Zhang, H. (2013) ‘Effects of Soret diffusion on the Laminar Flame Speed and Markstein length of Syngas/Air Mixtures’, *Proceedings of the Combustion Institute*, 34, pp. 695–702.

Ma, A., and Ong, A. (1985) ‘Pollution control in palm oil mills in Malaysia’ *Journal of the American Oil Chemists’ Society*, 62, pp. 261-266.

Ma, F., and Wang, Y., (2008) ‘Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine’, *Int J Hydrogen Energy*, 33, pp. 1416–1424.

Mameri, A., and Tabet, F. (2016) ‘Numerical investigation of counter-flow diffusion flame of biogas–hydrogen blends: Effects of biogas composition, hydrogen enrichment and scalar dissipation rate on flame structure and emissions’ *International Journal of Hydrogen Energy*, 41, pp. 2011–2022.

Manton, J., von Elbe, G., and Lewis, B. (1952) ‘Nonisotropic propagation of combustion waves in explosive gas mixtures and the development of cellular flames’ *J. Chem. Phys.*, 20, pp. 153–157.

Manton J., Von Elbe G and Lewis B. (1953), ‘Burning velocity measurements in a spherical vessel with central ignition’, *Proc. Combust. Inst.*, 4, pp. 358-363.

Markstein, G. H. (1949) ‘Cell structure of propane flames burning in tubes’, *J. Chem. Phys.*, 17, pp. 428–429.

McNaught, A.D., and Wilkinson, A. (1997), *Compendium of Chemical Terminology*, 2nd ed. , Blackwell Scientific Publications, Oxford.

Metghalchi, M., and Keck, J. C. (1980) 'Laminar burning velocity of propane-air mixtures at high temperature and pressure', *Combustion and Flame*, 38, pp. 143–154.

Miao, H. and Liu, Y. (2014) 'Measuring the Laminar Burning Velocity and Markstein Length of Premixed Methane/Nitrogen/Air Mixtures with the Consideration of Nonlinear Stretch Effects', *Fuel*, 121, pp. 208–215.

Miao J., Leung, C. W., Huang, Z. H., Cheung, C. S., Yu, H., and Xie, Y. (2009) 'Laminar burning velocities and Markstein lengths nitrogen diluted natural gas/hydrogen/air mixture at normal, reduced and elevated pressures', *International Journal of Hydrogen Energy*, 34, pp. 3145-3155.

Moghaddam, E. A., Ahlgren, S., Hulteberg, C., and Nordberg, Å. (2015) 'Energy balance and global warming potential of biogas-based fuels from a life cycle perspective', *Fuel Processing Technology*, 132, pp. 74–82.

MPOB. (2012). Oil palm and the environment. http://www.mpob.gov.my/en/palm-info/environment/520-achievements.

MPOC. (2011). Annual Report 2011 – The natural colours of health. http://mpoc.org.my/pubs_view.aspx?id=e488b7d8-4d94-4462-9443-e9dbd3d2441d.

Nonaka, H. O. B., and Pereira, F. M. (2016) 'Experimental and numerical study of CO_2 content effects on the laminar burning velocity of biogas' *Fuel*, 182, pp. 382–390.

Park, O., Veloo, P. S., Liu, N., and Egolfopoulus, F. N. (2011) 'Combustion characteristics of alternative gaseous fuels', *Proceeding of Combustion Institute*, 33, pp. 887-94.

Pizutti, L., Martins, C. A., and Lacava, P. T. (2016) 'Laminar burning velocity and flammability limits in biogas: A literature review', *Renewable and sustainable energy Reviews*, 62, pp. 856-865.

Qin, W., Egolfopoulos, F. N., and Tsotsis, T. T. (2001) 'Fundamental and environmental aspects of landfill gas utilization for power generation', *Chemical Engineering Journal*, 82(1-3), pp. 157-172.

Porpartham, E., Ramesh, A., and Nagalingam, B. (2007) ‘Effect of hydrogen addition on the performance of biogas fueled spark ignition engine’, *International Journal of Hydrogen Energy*, 32, pp. 2057-2065.

Radwan, M., Ismael, M., Younes Selim, M., Saleh, H., and Salem, H. (2001) ‘Laminar burning velocity of some coal derived fuels’, *Energy Sources Part A*, 23, pp. 345-361.

Rozenchan, G., Zhu, D. L., Law, C. K., and Tse, S. D. (2002) ‘Outward propagation, burning velocities, and chemical effects of methane flames up to 60 atm’, *Proceedings of the Combustion Institute*; 29, pp. 1461–1469.

Saqr, K. M., Kassem, H. I., Mohsin, M. S., and Wahid, M. A. (2010). ‘Ideal detonation characteristics of biogas-hydrogen and-hydrogen peroxide mixtures’ *Latest Trends on Theoretical and Applied Mechanics, Fluid Mechanics and Heat & Mass Transfer*, pp. 69-72.

Sankaran, R., Hawkes, E. R., Chen, J. H., Lu, T. F., and Law, C. K. (2007) ‘Structure of a spatially developing turbulent lean methane–air Bunsen flame’, *Proceedings of the Combustion Institute*, 31, pp. 1291–1298.

Schefer, R. W., Wicksall, D. M., and Agrawal, A. K. (2002) ‘Combustion of hydrogen-enriched methane in a lean premixed swirl-stabilized burner’, *Proceeding of the Combustion Institute*, 29, pp. 843-851.

Schoen, E. J., and Bagley, D. M.. (2012) 'Biogas Production and Feasibility of Energy Recovery Systems for Anaerobic Treatment of Wool-Scouring Effluent', *Resources, Conservation and Recycling*, 62, pp. 21-30.

Shafiee, S., and Topal, E. (2009) 'When will fossil fuel reserves be diminished?', *Energy Policy*, 37, pp. 181-189.

Smith, D., and Agnew, J .T. (1956) 'The effect of pressure on the laminar burning velocity of methane-oxygen-nitrogen mixtures', *Proc. Combust. Inst.*, 6, pp. 83-88

Smith, G. P., Golden, D. M., Frenklach, M., Moriarty, N. W., Goldenberg, B. E. M., and Bowman, C. T, et al. (1999) Gri-Mech 3.0, <http://www.me.berkeley.edu/gri_mech/>

Stone, R., Clarke, A., and Beckwith, P. (1998) 'Correlation for the laminar burning velocity of methane/diluent/air mixtures obtained from a free-fall experiments', *Combustion and Flame*;114, pp. 546-555.

Suhaimi, M. S., Saat, A., Wahid, M. A., Sies, M. M. (2016) 'Flame Propagation and Burning Rates of Methane-Air Mixtures Using Schlieren Photography' *JurnalTeknologi*, 78(10-2), pp. 21-27.

Takahashi, F., and Katta, V. R. (2005) 'Further studies on the reaction kernel structure and stabilization of jet diffusion flames', *Proceeding of the Combustion Institute*, 30, pp. 383-390.

Tang, C., Huang, Z., Jin, C., He, J., Wang, J., and Wang, X. (2008) 'Laminar burning velocities and combustion characteristics of propane-hydrogen-air premixed flames', *International Journal of Hydrogen Energy*, 33, pp. 4906-4914.

Taylor, S. C. (1991) 'Burning velocity and the effect of flame stretch', PhD Thesis. University of Leeds.

Vagelopoulos, C. M., and Egolfopoulos, F. N. (1998) 'Direct experimental determination of laminar flame speeds', *Proc. Combust. Inst.*, 27, pp. 513-519.

Vanag, V. K., Epstein, I. R. (2009) 'Cross-diffusion and pattern formation in reaction-diffusion systems', *Physical Chemistry Chemical Physics*; 11, pp. 897-912.

Verhelst, S., Woolley, R., Lawes, M., and Sierens, R. (2005) 'Laminar and unstable burning velocities and Markstein lengths of hydrogen–air mixtures at engine-like conditions', *Proc Combust Inst*, 30, pp. 209–16.

Walsh, J. L., Ross, C. C., Smith, M. S., Harper, S. R., and Wilkins W. A. (1988) ' Handbook on biogas utilization', *US Department of Energy*, Alabama.

Wei, Z. L, Leung, C. W., Cheung, C. S., and Huang, Z. H. (2016) 'Effects of H_2 and CO_2 addition on the heat transfer characteristics of laminar premixed biogas-hydrogen Bunsen flame', *International Journal of Hydrogen Energy*, 98, pp. 359-366.

Williams, F.A.: Combustion Theory, 2nd edition, Benjamin, 1985.

Wilson, D. A., and Lyons, K. M. (2009) 'On Diluted-Fuel Combustion Issues in Burning Biogas Surrogates', *Journal of Energy Resources Technology*, 131:4, 041802.

Wu, C. K., and Law C. K. (1984) 'On the determination of laminar flame speeds from stretched flames' *Proc. Combust. Inst.*, 20, pp. 1941-1949.

Xie, Y. L, Wang, J. H, Zhang, M., Gong, J., Jin, W., and Huang, Z. H. (2013) 'Experimental and Numerical Study on Laminar Flame Characteristics of

Methane Oxy-fuel Mixtures Highly Diluted with CO_2', *Energy and Fuel*, 27, pp. 6231-6237.

Zabetakis, M. G. (1965) 'Flammability characteristics of combustible gases and vapors', *U.S. Bureau of Mines Bulletin*.

Zahedi, P., and Yousefi, K. (2014) 'Effects of pressure and carbon dioxide, hydrogen and nitrogen concentration on laminar burning velocities and NO formation of methane–air mixtures', *J Mech Sci Technol*, 28(1), pp. 377–386.

Zeldovich, Y. B., Barenblatt, G. I., Librovich, V. B., and Makhviladze, G. M. (1985) 'Mathematical theory of combustion and explosions' Consultants Bureau.

Zeng, W., Liu, J., Ma, H., Liu, Y., Liu, A. (2018) 'Experimental study on the flame propagation and laminar combustion characteristics of landfill gas' *Energy*, 158, pp. 437-448.

Zhang, J., Hu, T., Lv, H., Dong, C. (2016). 'H-abstraction mechanisms in oxidation reaction of methane and hydrogen: A CASPT2 study', *International Journal of Hydrogen Energy*, 41, pp.12722-12729

Zhang, Y., Yan, L., Chi, L., Long, X., Mei, Z., and Zhang, Z. (2008) 'Startup and operation of anaerobic EGSB reactor treating palm oil mill effluent', *Journal of Environmental Sciences*, 20, pp. 658-663.

Zhen, H. S, Leung, C. W., and Cheung, C. S. (2013) 'Effects of hydrogen addition on the characteristics of a biogas diffusion flame', *International Journal of Hydrogen Energy*, 38, 6874-6881.

Zhen, H. S, Leung, C. W., Cheung, C. S., and Huang, Z. H. (2014) 'Characterization of biogas-hydrogen premixed flames using Bunsen burner', *International Journal of Hydrogen Energy*, pp. 13292-13299.

Zhen, H. S., Leung, C. W., Cheung, C. S., and Huang, Z. H. (2016) 'Combustion characteristics and heating performance of stoichiometric biogas-hydrogen-air flame', *International Journal of Heat and Mass Transfer*, 92, pp. 807-814.

Appendix A Calculation of Fuel and Air Partial Pressure

ϕ	BG50	mole fraction	BG60	mole fraction	BG80	mole fraction
0.6	CH_4	0.056				
	CO_2	0.056				
	O_2	0.187				
	N_2	0.701				
0.7	CH_4	0.064		0.066		0.067
	CO_2	0.064		0.044		0.017
	O_2	0.183		0.187		0.134
	N_2	0.689		0.703		0.782
0.8	CH_4	0.072		0.074		0.076
	CO_2	0.072		0.049		0.019
	O_2	0.18		0.184		0.152
	N_2	0.676		0.693		0.753
0.9	CH_4	0.079		0.082		0.085
	CO_2	0.079		0.054		0.021
	O_2	0.177		0.181		0.169
	N_2	0.665		0.683		0.725
1	CH_4	0.095		0.089		0.093
	CO_2	0.095		0.06		0.023
	O_2	0.17		0.179		0.186
	N_2	0.64		0.672		0.698
		1				1
1.1	CH_4					0.101
	CO_2					0.025
	O_2					0.202
	N_2					0.672

Appendix B Apparatus

Figure B1 Ignition control box.

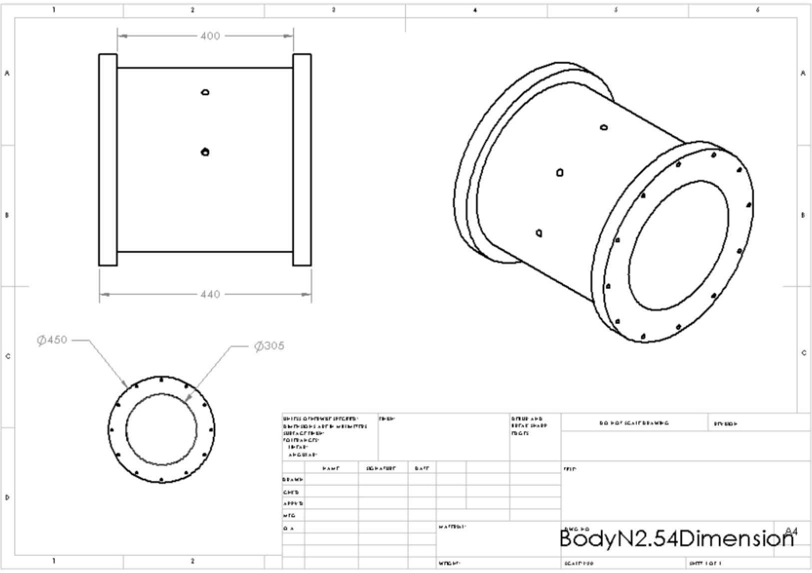

Figure B2 CVCC body dimension in millimeter.

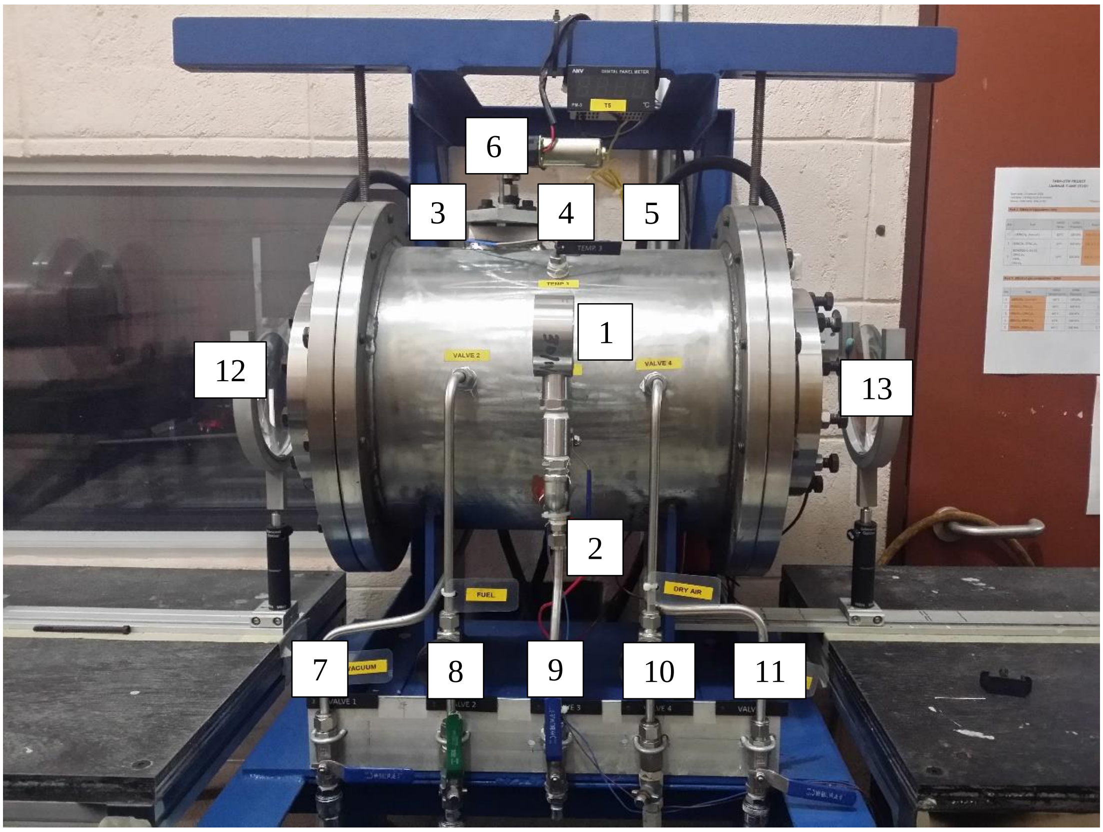

Figure B3 CVCC with all the lines and instrumentation.

1. Pressure gauge
2. Electrode
3. Thermocouple 1
4. Thermocouple 2
5. Thermocouple 3
6. Mixer motor
7. Vacuum line
8. Fuel line
9. Exhaust line
10. Dry air line
11. Compressed air line
12. Collimating lens
13. Decollimating lens

LIST OF PUBLICATIONS

1. Flame propagation and burning rates of methane-air mixtures using schlieren photograph. (2016). Jurnal Teknologi 78/21-27.
2. Flammability and burning rates of low quality biogas at atmospheric condition. (2017). Jurnal Teknologi 79/15-20
3. The effects of CO_2 variation on hydrodynamic and thermal diffusive stability of biogas-air flame. (2018). Journal of Advanced Research in Fluid Mechanics and Thermal Sciences.Volume 52, Issue 2246 – 258.