

THE ENHANCEMENT OF RESIDUAL ELECTRIC FIELD IN WATER
ELECTROLYSIS BY GREEN LASER IRRADIATION

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..to all who love me, I love you too...

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ABSTRACT

Hydrogen energy produced by water electrolysis is considered free from green house effect. However such production still lacks in efficiency. Therefore we proposed an efficient system to increase the hydrogen production by introducing a green laser in the water electrolysis system. In this work a diode-pumped solid state laser operating in second harmonic generation (green laser) was employed as a source of external electric field. The green laser was illuminating directly into a water electrolysis chamber. The power of the laser was varied in the range of 0 to 200 mW. Conventional electrolysis and electrolysis using white light from halogen lamp were also conducted for comparison purposes. The effect of green laser was further characterized based on beam direction, angle and displacement. The direction of the beam was set either in direction or in opposite direction to the electric field. The beam angle was varied in the range from 0° to 180° and the displacement is varied within 0 to 6 mm from the end of electrode. The result obtained showed that the hydrogen production corresponding to green laser electrolysis is dependent on the power of the laser. Higher laser power will contribute to higher hydrogen production. The rate of hydrogen production is 1.17 ml min^{-1} with green laser, 0.80 ml min^{-1} in response to white light and 0.67 ml min^{-1} for conventional electrolysis. The rate of hydrogen production is 1.33 ml min^{-1} when light is illuminated from cathode to anode (in direction with residual electric field) and $0.267 \text{ ml min}^{-1}$ in the opposite direction. The hydrogen production is found inversely proportional with regard to beam angle. When the angle of irradiation is increased, the hydrogen production rate decreases. Besides, the highest hydrogen production can be achieved when the beam displacement is at zero distance from the electrodes. This means that the beam essentially connects the end of electrodes that allows fast flow of current of the closed electric circuit in the electrolysis system. In conclusion, green laser has positive impact on the hydrogen production because it contributes extra electric field to enhance the weak residual electric field caused by the polarizability property of water.

ABSTRAK

Tenaga hidrogen dihasilkan dari elektrolisis air dianggap bebas dari kesan rumah hijau. Walau bagaimanapun penghasilan sebegini masih kurang efisien. Oleh kerana itu kami mengusulkan sistem yang efisien untuk meningkatkan penghasilan hidrogen dengan menggunakan laser hijau dalam sistem elektrolisis air. Dalam kajian ini laser berkeadaan pepejal dipam-diod yang beroperasi pada generasi harmonik kedua (laser hijau) telah digunakan sebagai sumber medan elektrik luar. Laser hijau telah disinari terus ke dalam kebuk elektrolisis air. Kuasa laser telah dipelbagaikan dalam lingkungan 0 hingga 200 mW. Elektrolisis konvensional dan elektrolisis menggunakan cahaya putih dari lampu halogen juga telah dijalankan untuk tujuan perbandingan. Kesan laser hijau selanjutnya dicirikan berdasarkan arah alur, sudut, dan sesaran. Arah pancaran telah ditetapkan sama ada searah atau bertentangan dengan medan elektrik. Sudut pancaran telah diubah dalam julat dari 0° hingga 180° dan anjakan diubah antara 0 hingga 6 mm dari hujung elektrod. Keputusan yang diperolehi menunjukkan bahawa pengeluaran hidrogen berhubungan dengan elektrolisis laser hijau bergantung kepada kuasa laser. Kuasa laser yang tinggi akan menyumbang penghasilan hidrogen yang tinggi. Kadar penghasilan hidrogen ialah 1.17 ml min^{-1} dengan laser hijau, 0.80 ml min^{-1} sebagai tindak balas kepada cahaya putih dan 0.67 ml min^{-1} untuk elektrolisis konvensional. Kadar pengeluaran hidrogen ialah 1.33 ml min^{-1} apabila cahaya menerangi dari katod ke anod (searah dengan medan elektrik sisa), dan $0.267 \text{ ml min}^{-1}$ dalam arah yang bertentangan. Pengeluaran hidrogen didapati berkadar songsang terhadap sudut pancaran. Apabila sudut pancaran bertambah, kadar penghasilan hidrogen bertambah. Selain itu, penghasilan hidrogen yang tinggi juga boleh diperolehi apabila sesaran alur adalah pada jarak kosong dari elektrod. Ini bermaksud alur bertindak sebagai penyambunghujung elektrod yang membolehkan arus mengalir laju dalam litar elektrik yang tertutup dalam sistem elektrolisis. Sebagai kesimpulan, laser hijau mempunyai impak positif ke atas pengeluaran hidrogen kerana ia menyumbang medan elektrik tambahan untuk meningkatkan medan elektrik sisa yang lemah disebabkan oleh sifat kepolaran air.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	x
	LIST OF FIGURES	xi
	LIST OF ABBREVIATIONS	xvi
	LIST OF SYMBOLS	xviii
	LIST OF APPENDICES	xx
1	INTRODUCTION	1
	1.1 Background of Study	1
	1.2 Problem Statement	6
	1.3 Objectives	7
	1.4 Scope of Work	7
	1.5 Significances and Original Contributions of This Study	8
	1.6 Thesis Structure and Organization	8

2	LITERATURE REVIEW	10
	2.1 Literature Review	10
	2.2 Water Electrolysis Revolution	11
	2.2.1 Electrolytes and Additives	12
	2.2.2 Electrode Material	14
	2.3 Climate Change and Global Warming	15
	2.4 Hydrogen Production Method	18
	2.4.1 Current Method	19
	2.4.2 Methods under Development of Water Splitting	23
	2.5 Water Molecule Structure and Its Properties	32
	2.5.1 Dipole Moment of Water	34
	2.5.2 Hydrogen Bond in Water	37
	2.6 Polarization	38
	2.6.1 Polarization of Water	39
	2.6.2 Polarization in Aqueous Sodium Chloride	40
	2.7 Faraday's Law of Electrolysis	43
3	METHODOLOGY	45
	3.1 Introduction	45
	3.2 Experimental Setup of Electrolysis Cell	46
	3.3 Materials and Apparatus	48
	3.3.1 Salt Catalyst	49
	3.3.2 Ethanol as an Electron Donor	52
	3.3.3 Graphite as an Inert Electrode	52
	3.4 Green Laser Irradiation in Electrolysis System	58

4	RESULTS AND DISCUSSIONS	74
4.1	Overview	74
4.2	Hydrogen Bubbles Effect	75
4.3	Catalyst and Additive	78
4.4	The Effect of Green Laser on Hydrogen Production	85
4.4.1	The Position of Laser Beam Irradiation	91
4.4.2	The Direction of Laser Beam Irradiation	96
4.4.3	Radial Direction of Laser Beam Irradiation	98
4.5	Hydrogen Gas Test	105
4.5.1	Burning Splint Test	105
4.5.2	Residual Gas Analysis	106
4.6	The Increases of Temperature and Current Flow During Electrolysis	111
5	CONCLUSION	114
5.1	Conclusion	114
5.2	Suggestion and Further Research	117
	REFERENCES	119
	Appendices A-J	127-136

LIST OF TABLES

TABLE NO.	TITLE	PAGE
1.1	Technical Comparison of Hydrogen Liquid with Other Fuels(Rand and Dell, 2008).	4
3.1	Physical and chemical properties of NaCl and Na ₂ SO ₄ (Sarada, 1990).	51
3.2	Physical properties of molybdenum (International Molybdenum Association IMO A)	56
3.3	Cirrus 2 Atmospheric pressure gas monitor specifications (Cirrus 2 RGA)	72

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	A sustainable Hydrogen Energy chart (Blocks <i>et al.</i> , 2008).	2
2.1	The greenhouse effect due to natural events and human activities (Marc, 2015).	17
2.2	Some feedstocks of hydrogen and the alternatives processes (Riis and Hagen, 2006).	18
2.3	Hydrogen production flow via steam reforming method (Takamura, 2002).	20
2.4	Chlor-alkali process of sodium chloride aqueous solution as an example of waste stream hydrogen process (Dow-Mitsui Chlor-Alkali Facility, 2010).	21
2.5	Partial oxidation process to produce hydrogen gas (Walker, 2013).	23
2.6	A schematic diagram of alkaline electrolyzers (Riis and Hagen, 2006).	26
2.7	Main components of alkaline fuel cell in industries (Konrad, 2013).	26
2.8	Palladium electrolyzers for hydrogen purification (Choi <i>et al.</i> , 2005).	28
2.9	The schematic diagram of high temperature in a solid oxide electrolyzer cell (Robert <i>et al.</i> , 2012).	29
2.10	A conventional photovoltaic-electrolyzer system for hydrogen production – a non-optimized PV power supply (Thomas <i>et al.</i> , 2008).	31

2.11	Tetrahedral arrangement of a water molecule.	33
2.12	Schematic diagram of water molecule and its lone pairs (Cruzan, 2012).	34
2.13	The net dipole moment in (a) water molecule and (b) carbon dioxide.	36
2.14	Hydrogen bond between water molecules (Millan and Klos, 2013).	38
2.15	Schematic diagram of atomic interaction between Na^+ and Cl^- ions of table salt with water molecule (Michelle, 2012).	42
3.1	Research flowchart of hydrogen production by water electrolysis.	46
3.2	Schematic diagram of general electrolysis.	47
3.3	Green laser was employed during electrolysis.	48
3.4	Types of salt that is being used such as (a) sodium chloride and (b) sodium sulphate.	50
3.5	Hexagonal structure of carbon bond in graphite (Dmitri, 2013).	54
3.6	(a) A graphite bar is used as cathode and anode electrode and each electrode is placed (b) inside a 15 ml test tubes.	55
3.7	Molybdenum sheet is used as sacrifice agent (catalyst) during electrolysis.	57
3.8	DPSS laser operating at wavelength of 532 nm.	59
3.9	Power stability of diode-pumped solid state laser 532 nm.	59
3.10	The green laser irradiation is illuminates horizontally to the electrolysis cell from cathode to anode direction.	61
3.11	Laser beam line irradiation that parallel to the graphite electrodes	63
3.12	Laser beam line irradiation that perpendicular to the graphite electrodes.	64
3.13	The vertical angle of laser beam line to the electrodes.	65

3.14	Variable distances of green laser beam line aligned horizontally from the electrodes end.	66
3.15	The real-time image of hydrogen bubbles captured by CCD camera during laser electrolysis	67
3.16	The experimental setup for hydrogen gas using CCD camera (a) as illustrated in diagram and (b) in real view.	68
3.17	Experimental set up to collect the gas at cathode terminal for residual gas analysis	70
3.18	A system of residual analysis gas consisting (a) a Residual Gas Analysis / Mass Spectrometry Cirrus 2 that is monitored through (b) a personal computer installed with Process Eye Professional software to analyze the composition of sampling gas inside the (c) Tedlar gas bag.	71
3.19	An analysis of the gas composition with respect to time by using Process Eye Professional.	73
4.1	(a) Top view : hydrogen bubbles is dispersed in the water that cause the unclear view of water, and (b) Side view: by placing the electrodes inside the test tubes, few bubbles are dispersed into the water.	76
4.2	Bubble effects due to bubbles dispersion in electrolyte and bubbles coverage on electrode surface	77
4.3	A graph of volume of hydrogen (ml) versus time (minutes) that corresponds to different salt (catalyst) used during conventional electrolysis.	79
4.4	Polarization of water and residual electric field (REF) in response to catalyst Na^+ and Cl^- ion.	83
4.5	A graph of volume of hydrogen (ml) versus time (minutes) that correspond to various amount of ethanol as an electron donor.	84
4.6	The intensity of laser irradiation 532 nm passing through three different medium; (a) in air, (b) after passing the empty beaker, and (c) after passing beaker contained aqueous NaCl solution.	87

4.7	A graph of volume of hydrogen (ml) versus time (minutes) in respond to different light irradiation source during electrolysis.	89
4.8	Hydrogen bubbles captured via CCD camera at cathode terminal of (a) a conventional electrolysis and (b) laser electrolysis, both images is captured at time at 1 minute. The images captured showed that the greater amount of hydrogen bubbles yield during laser electrolysis.	91
4.9	A graph of volume of hydrogen (ml) versus time (minutes) at different distance of laser beam irradiation to the electrodes.	92
4.10	A graph of rate of hydrogen production with respect to the distance between laser beam line and the electrodes.	94
4.11	The charges motion in the electric field (a) when electron move faster and strong because the electric force parallel with the electric field induced by the laser beam. (b) the electron motion retarded because the electric force bending or inclined at angle θ toward anode.	95
4.12	A graph of volume of hydrogen (ml) versus time (minutes) with the presence of laser beam direction from cathode to anode, and vice versa.	97
4.13	A graph of volume of hydrogen (ml) versus time (minute) that correspond to different angle of laser beam irradiation direction.	99
4.14	A graph of the rate of hydrogen production with respect to different angle of laser beam irradiation.	100
4.15	A graph of volume of hydrogen (ml) versus time (minute) that correspond to laser beam irradiation that is at vertical (parallel to electrodes) and horizontal (perpendicular to electrodes).	102
4.16	The direction of laser beam is correspond to direction of external electric field.	103

4.17	Polarization of water and Na^+ and Cl^- ions in response to residual electric field REF at (a) laser beam directed parallel to residual electric field and (b) laser beam direction anti-parallel to residual electric field.	104
4.18	A burning splint test of hydrogen gas inside a test tube.	106
4.19	A graph of pressure (mTorr) versus elapsed time (hh:mm:ss) of the sample gas analysis by using residual gas analyzer.	109
4.20	The composition of hydrogen gas during residual gas analysis. Hydrogen is denoted at mass two (M2) in the graph of pressure (mTorr) versus the atomic mass units (amu)	110
4.21	The changes of solution temperature and current flow during laser electrolysis	112
4.22	The increases of temperature during electrolysis with respect to time with and without the presence of laser irradiation.	113

LIST OF ABBREVIATIONS

AFC	-	Alkaline fuel cell
BCC	-	Body-centered cubic
c-Si	-	Crystalline silicon
CCD	-	Charged-coupled device
DC	-	Direct current
DPSSL	-	Diode-pumped solid state laser
EDTA	-	Adetate disodium
GHG	-	Greenhouse gas
HB	-	Hydrogen bonding
HE	-	Hydrogen energy
HFCs	-	Hydrofluorocarbons
HP	-	Hydrogen production
HTE	-	High temperature electrolysis
KTP	-	Potassium titanyl phosphate
MHD	-	Magnetohydrodynamics
Nd:YAG	-	Neodymium-doped yttrium aluminium garnet
Nd:YVO ₄	-	Neodymium-doped yttrium orthovanadate
NTP	-	Normal temperature and pressure
PEM	-	Proton exchange membrane
PFCs	-	Perfluorocarbons
POX	-	Partial oxidation
ppb	-	Part per billions
PTFE	-	Polytetrafluoroethylene
PTL	-	Porous transport layer

PV	-	Photovoltaic
PVF	-	Polyvinyl fluoride
REF	-	Residual electric field
RGA	-	Residual gas analysis
SOES	-	Solid oxide electrolyzer cell
STP	-	Standard temperature and pressure
USD	-	United States dollar
WMO	-	World Meteorologica Organization

LIST OF SYMBOLS

μ	-	Dipole moment
aq	-	Aqueous
Au	-	Aurum
B	-	Magnetic field
C	-	Graphite / carbon
C_2H_4O	-	Acetaldehyde
C_2H_5OH	-	Ethanol
C_F	-	Faraday constant
CH_4	-	Methane
Cl^-	-	Chloride ion
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
D	-	Dielectric displacement
E	-	Electric field
F	-	Ionic force
H^+	-	Hydrogen ion
H_2	-	Hydrogen molecule
H_2SO_4	-	Sulfuric acid
I	-	Intensity of laser light
i	-	Current
Ir	-	Iridium
it	-	Current per unit time
j	-	Current density
KOH	-	Potassium hydroxide
M	-	Molar mass of substances

m	-	Mass of the substance being transferred
Mo	-	Molybdenum
Na^+	-	Sodium ion
Na_2SO_4	-	Sodium sulphide
NaCl	-	Sodium chloride
NaOH	-	Sodium hydroxide
Ni	-	Nickel
NiO	-	Nickel(II) oxide
O^{2-}	-	Oxygen ion
P	-	Polarization
Pb	-	Plumbum
Pt	-	Platinum
Q	-	Total electric charge passed through substance
q	-	Charged particles
r	-	Distance between charged particles
Rh	-	Rhodium
Ru	-	Ruthenium
SF_6	-	Sulphur hexafluoride
Ti	-	Titanium
TiO_2	-	Titanium oxide
v	-	Charged particle velocity
V_2O_5	-	Vanadium(V) oxide
x	-	Electronegativity difference
z	-	Valency number
Z	-	Electrochemical equivalent
Zr	-	Zirconium
δ^-	-	Electronegative end
δ^+	-	Electropositive end
θ	-	Angle
χ_e	-	Electric susceptibility

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Chemical and physical properties of water molecule	127
B	Specification of CCTV lens	128
C	Publications	129
D	Milwaukee MW 102 pH/Temperature Meter	130
E	Metrolab 3-Axis Teslameter	131
F	Table For Graph In Figure 4.3	132
G	Table For Graph In Figure 4.7	133
H	Table For Graph In Figure 4.9	134
I	Table For Graph In Figure 4.12 and 4.13	135
J	Table For Graph In Figure 4.22	136

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Hydrogen (H₂) is known as the most abundant element in the universe. On earth, hydrogen can be found combined with other elements; it combined with oxygen in the water while as in petroleum, natural gas and coal, hydrogen combined with carbon. However, hydrogen is not a primary energy source, but a secondary energy vector (so-called energy carrier). This means that it has to be produced from one of the primary energy sources (Winterand Nitsch, 1988).

Hydrogen is a clean form of energy carrier that can be produced using many different primary sources of energy. Hydrogen, together with fuel cell, which are very efficient energy conversion devices, is attracting the attention of public authorities and private industry nowadays. There are three primary energy sources (Riis and Hagen, 2006);

1. Renewable energy - direct solar, biomass, solar photovoltaic, wind, geothermal,
2. Nuclear energy, and
3. Fossil fuels - coal, oil (heavy residues and other petroleum fractions), natural gas.

All the energy we use, including hydrogen, must be produced from one of these three primary energy resources. By using chemical, thermal or electrical energy, the energy from primary sources can be stored in hydrogen. Figure 1.1 shows a diagram of various primary energy sources that can be used for the production of hydrogen. This proposition is called Hydrogen Economy, HE (Blocks *et al.*, 2008). Some related issues of hydrogen energy are regarding security of energy supply, climate change reduction, atmospheric pollution control, and electricity generation.

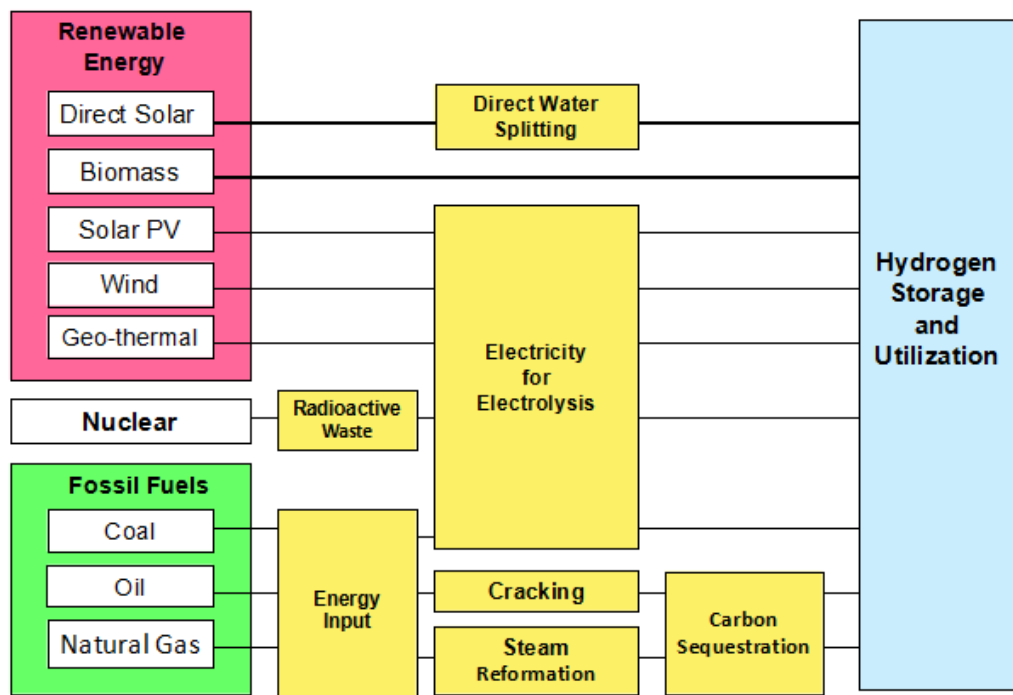


Figure 1.1 A sustainable Hydrogen Energy chart (Blocks *et al.*, 2008).

Hydrogen would be made available through the splitting of water into its elements making it long-term and renewable energy sources. In addition, this hydrogen would recombine with oxygen in the air to discharge this energy, so that water would be returned to the atmosphere as part of the natural water cycle. This is the reason why water splitting process is called carbon neutral process and sustainable technology. There are great challenges for hydrogen as an energy carrier since it is not fully developed yet over the world. Many countries are in struggling mode to develop the hydrogen economy as there are a number technological and non-technical barriers need to be addressed.

The basic physical properties of hydrogen are it is a colourless, odourless, tasteless and non-toxic gas. Table 1.1 shows a comparison of hydrogen and other fuels available. From the table, liquid hydrogen boils at $-252.77\text{ }^{\circ}\text{C}$, and it has a density of 70.99 g/m^3 . Thus, with these properties, hydrogen has the highest energy-to-weight ratio to compare with of all fuels: 1 kilogram (kg) of hydrogen has the same amount of energy as 2.1 kg of natural gas or 2.8 kg of gasoline. Hydrogen burns in air at concentrations in the range of 4 to 75 % by volume while methane burns at 5.3 to 15 % concentrations by volume. The highest burning temperature of hydrogen is $2318\text{ }^{\circ}\text{C}$ and is reached at 29% concentration by volume in air (Rand and Dell, 2008).

Hydrogen H_2 is the lightest molecules above others with molecular weight equal to 2.0016 and densities of hydrogen gas is 0.0899 kg/m^3 . Due to its low density, hydrogen liquid weighs is lower than petroleum-based fuels. The hydrogen liquid has a very low boiling point that is 20 K, so that it requires fairly sophisticated equipment for preparation process and maintenance if hydrogen is to be employed as an energy vector and also a non-polluting fuel in future (Elin *et al.*, 2010).

Table 1.1: Technical Comparison of Hydrogen Liquid with Other Fuels(Rand and Dell, 2008).

	Hydrogen	Petroleum	Methanol	Methane	Propane	Ammonia
Boiling point (K)	20.3	350-400	337	111.7	230.8	240
Liquid density (kgm ⁻³), NTP*	70.8	702	797	425	507	771
Gas density (kgm ⁻³), NTP*	0.0899			0.718	2.01	0.77
Heat vaporization (kJkg ⁻¹)	444	302	1168	577	388	1377
Higher heating value/mass (MJkg ⁻¹)	141.9	46.7	23.3	55.5	48.9	22.5
Lower heating value/mass (MJkg ⁻¹)	120	22.38	20.1	50	46.4	18.6
Lowerheatingvalue/liquid/volume (MJm ⁻³)	8520	31170	16020	21250	23520	14350
Diffusivity in air (cm ² s ⁻¹)	0.63	0.08	0.16	0.2	0.1	0.2

Lower flammability limit/vol. % (in air)	4	1	7	5	2	15
Upper flammability limit/vol. % (in air)	75	6	36	15	10	28
Ignition temperature in air (°C)	585	222	385	534	466	651
Ignition energy (mJ)	0.02	0.25		0.3	0.25	
Flame velocity (cms ⁻¹)	270	30		34	38	

1.2 Problem Statement

Hydrogen energy has a high potential as an energy carrier in future. The current available methods on producing hydrogen has many drawbacks such as the release of greenhouse gaseous (GHG). Uncontrol released of GHG to atmosphere would lead to serious issues related to climate change effects due to active industrial activities (Judith, 2010). Currently, almost all hydrogen (approximately to 78 %) is manufactured through reforming of hydrocarbons (natural gas and petroleum). This process has low energy-conversion efficiency and contributes about 8.8 tonnes of CO₂ gas emission annually (Rand and Dell, 2008). Other method on producing hydrogen is through coal gasification that contributes to 18 % of hydrogen energy. This method produces more pollution due to GHG emissions than petroleum and needed high cost maintenance. In fact, the energy sources mentioned would eventually become limited by time as the sources are non-renewable. The remaining 4 % of hydrogen energy were from electrolysis process. There are several types of water electrolysis available such as photobiological electrolysis (using algae bioreactor), biocatalysed electrolysis (using microbes) and photocatalytic electrolysis (also known as electrolytic, that using semiconductor material as an electrodes and solar energy as a source of energy). All this processes are dependant to nature in terms of energy source to initiate the process, as well as the organisms. In this attempt, laser electrolysis is introduced as a new technique of electrolysis that is more convenient light source to compare with solar energy for commercial electrolysis. Although electrolysis gives a small proportion in hydrogen production by using current method, we believed that this process would contributes a lot to society if the existing methods are upgraded with suitable materials and substances.

1.3 Objectives

The main objective of this research is to develop an efficient water electrolysis system by using laser to enhance the residual electric field. In order to achieve the main objective of the research, following tasks are performed;

1. To construct the water electrolysis reactor and optimize the electrolysis parameters.
2. To optimize the electric field induced by diode-pumped solid state laser including the direction and distance upon electrodes position and the power of green laser.
3. To characterize the effect of residual electric field on hydrogen production efficiency.

1.4 Scope of Work

Initially, the electrolysis chamber was set up based on the basic electrolysis circuit. Graphite (C) rod was used as the electrodes throughout the experiment. The distance between two electrodes is fixed to a certain distance. In order to increase the area of electrode, molybdenum was added into the electrolysis cell. Distilled water was added with sodium chloride (NaCl) to become an electrolyte for electrolysis process and ethanol to act as electron donor. Electric power supply was used to supply electric charge to initiate the electrolysis. Diode pumped solid state laser with second harmonic generation was employed as a source of laser electrolysis. The gas yield during the electrolysis is collected inside a test tube contained the graphite electrodes.

1.5 Significant and Original Contribution of This Study

This research is carried out to investigate the influence of green laser irradiation to electrolysis efficiency during water electrolysis. Conventional electrolysis usually takes longer time to produce hydrogen, while in industrial hydrogen manufacture, the high production cost and environmental problems are unavoidable. By introducing laser electrolysis (an employment of laser as a light source during water electrolysis), the weak residual electric field during conventional electrolysis can be solved. This is due to the coherent properties of the laser light that related to the polarization of the light. As the polarization of the laser light is high, the amplitude of the electric field carried by the laser is high. Thus, the hydrogen production during laser electrolysis could be enhanced. It is considered as an efficient method in producing pure hydrogen for commercial purposes.

1.6 Thesis Structure and Organization

This thesis consists of five chapter including the introduction, literature review, methodology, result and discussion, and conclusion. The first chapter will introduce briefly about the hydrogen research. The advantages and disadvantages regarding hydrogen energy are described. Furthermore, the objectives of the research, problems regarding this topic, and the scope of the research are discussed.

The literature reviews on previous study about hydrogen production using various methods are discussed in Chapter 2. Besides, the fundamental theories of water electrolysis process are discussed in details. The discussion consist the water properties as abundant source in hydrogen production industry, current and under development methods of hydrogen production, and diode pump solid state laser working principle that is proposed in laser electrolysis.

Chapter 3 describes the research methodology; where the apparatus and materials used to build the electrolysis cell are explained in detail. The discussion includes the variable parameters to enhance the hydrogen production such as the type of catalysts that being used, ethanol, molybdenum, and the electrodes. Other than that, the laser properties that are being studied for laser electrolysis is discussed in details.

The results and discussion are presented in Chapter 4 including the explanation of the effect of green laser irradiation during laser electrolysis and how green laser react with water molecules and increased the electrolysis efficiency.

Overall work done during this research is summarized in Chapter 5. The problems encountered during experiment are discussed and the solutions to overcome the problems that would increase the value added of the findings are suggested.

REFERENCES

- Abouatallah, R. M., Kirk, D. W., Thorpe, S. J., and Graydon, J. W. (2001). Reactivation of Nickel Cathodes by Dissolved Vanadium Species During Hydrogen Evolution in Alkaline Media. *Electrochim. Acta*. 47: 613-621.
- Akimoto, A., Maeda, K., and Ozaki, N. (2013). Hydrogen Generation by Laser Irradiation of Carbon Powder in Water. *The Journal of Physical Chemistry*. 117(36): 18281-18285.
- Andreas, Z., Andreas, B., and Louis, S. (Eds.) (2008). *Hydrogen as a Future Energy Carrier*. Federal Republic of Germany. Wiley-VCH.
- Andrew, F., Elizabeth, C., Carroll, Delmar, S., Larsen, Michael, S., Nigel, Browning, D., and Osterloh, E. (2008). First Demonstration of CdSe as a Photocatalyst for Hydrogen Evolution from Water under UV and Visible Light. DOI: 10.1039/b718796c, Berkeley, CA, USA.
- Andrew, J. L., and Harry, A. A. (2010). Water-Splitting Photoelectrolysis Reaction Rate via Microscopic Imaging of Evolved Oxygen Bubbles. *Journal Electrochem. Soc.* 2010. 157(9): 1-3.
- Andrews, C. C., and Murphy, O. J. (2003). *MSC-23045*. Retrieved on July 18, 2014, from <http://ntrs.nasa.gov/>
- Anup Shah (2013, November 11). Climate Change And Global Warming Introduction. *Global Issues*. Retrieved November 21, 2013, from <http://www.globalissues.org/>
- Block, D and Raissi, A (2008). *Hydrogen Research at Florida Universities – Final Report*. Unpublished note, Florida Solar Energy Center.
- Bommaraju, T. V., Orosz, P. J., and Sokol, E. A. (2007). Brine Electrolysis. *Electrochemistry Encyclopedia*. Cleveland: Case Western Reserve University.

- Bououdina, M., Grant, D., and Walker, G. (2006). Review on Hydrogen Absorbing Materials—Structure, Microstructure, and Thermodynamic Properties. *International Journal Hydrogen Energy*.31(2): 177–182.
- Bund, A., Koehler, S., Kuehnlein, H. H., Plieth, W. (2003). Magnetic Field Effects in Electrochemical Reactions. *Electrochim.Acta*.2003; 49: 147-152.
- Carmo, M., Fritz, D., Mergel, J., and Stolten, D. (2013).A Comprehensive Review on PEM Water Electrolysis. *International Journal of Hydrogen Energy*. 38(12): 4901-4934.
- Cavendish, F. R. S. (1683-1775). Three Papers, Containing Experiment on Factitious Air by H. Philosophical Transactions.56, 1766-01-01. 56:141–184.
- Chen, C., Spliethoff, H., Yang, L. B., and Andries, J. (2003). Hydrogen Production from Gasification–Pyrolysis Of Biomass. III. *International Slovak Biomass Forum*. 3–4 February. Bratislava, 36–40.
- Chen, Y. X., Lavacchi, A., Miller, H. A., Bevilacqua, M., Filippi, J., Innocenti, M., Marchionni, A., Oberhauser, W., Wang, L., and Vizza, F. (2014). Nanotechnology Makes Biomass Electrolysis More Energy Efficient Than Water Electrolysis. *Nature Communications*.5: 4036.
- Choi, P., Jalani, N. H., and Datta, R. (2005).Thermodynamics and Proton Transport in Nafion – I. Membrane Swelling, Sorption, and Ion Exchange Equilibrium. *Journal of the Electrochemical Society*.152(3) : E84 – E89.
- Cramer, W. (2014). *Executive Summary, Chapter 18: Detection and Attribution of Observed Impacts*. p 982-984, IPCC AR5 WG2 A.
- Deluga, G. A., Salge, J. R., Schmidt, L. D., and Verykios, X. E. (2004).Renewable Hydrogen from Ethanol by Autothermal Reforming. *Science Mag*. 303, 993.
- Demirbas, M. F. (2006). Hydrogen from Various Biomass Species Via Pyrolysis and Steam Gasification Processes. *Energy Sources, Part A*. 28, 245–252.
- Dincer, I., and Joshi, A. S. (Eds.) (2013). *Solar Based Hydrogen Productions Systems*. London: Springer
- Dmitri, K. (2013, June 22). Graphite. *Substances and Technologies*, Retrieved December 12, 2013, from <http://www.substech.com>.

- Ehl, R. G., and Ihde, A. (1954). Faraday's Electrochemical Laws and the Determination of Equivalent Weights. *Journal of Chemical Education*. 31: 226–232.
- Elin, Y., Insan, K., and Zaki, S. (2010). Hydrogen Gas Production from Nuclear Power Plant in Relation to Hydrogen Fuel Cell Technologies Nowadays. *AIP Conference Proceeding*. 1244 (1): 70-82.
- Emmanuel, Z., Elli, V., and Nicolaos, L. (2004). A Review on Water Electrolysis. *TCJST*. 4(2): 41-71.
- Endres, F., and El Abedin, S. Z. (2006). Air and water stable ionic liquids in physical chemistry. *Physical Chemistry Chemical Physics*. 8(18): 2101-2116.
- Freude, D. (2005). Molecular Physics: Chapter 3 - Molecules in Electric and Magnetic Fields. Chapter Fields: 1-26.
- Gibson, T. L., and Kelly, N. A. (2008). Optimization of Solar Powered Hydrogen Production Using Photovoltaic Electrolysis Devices. *International J. of Hydrogen Energy*. 33: 5931-5940.
- Grigoriev, S. A., Poremsky, V. I., and Fateev, V. N. (2006). Pure Hydrogen Production by PEM Electrolysis for Hydrogen Energy. *International Journal of Hydrogen Energy*. 31(2): 171–175.
- Ismail, A. A., and Detlef, W. B. (2014). Photochemical Splitting of Water for Hydrogen Production by Photocatalysis: A Review. *Solar Energy Materials and Solar Cells*. 128: 85–101.
- John. T., George, S., Margeret, K. M., Pin, C. M., Ben, K., Maria, G., Robert, J. E., and Dan, B (2008). Renewable Hydrogen Production. *International Journal Energy Research*. 32(5): 379 – 407.
- Judith L. (2010). Cycles and Trends in Solar Irradiance and Climate. *Wiley Interdisciplinary Reviews: Climate Change*. 1: 111-122.
- Kirby, B. J. (2010). Micro- and Nanoscale Fluid Mechanics : Transport In Microfluidic Devices. New York, Cambridge University Press.
- Kitazawa, D., Fujino, M., and Aoba, S. (2010). Treatment of Waste Seawater by Electrolysis Using Charcoal Electrodes. OCEANS'10 Sydney: IEEE, 1-5.

- Kiuchi, D., Matsushima, H., Fukunaka, Y., and Kuribayashi, K (2006). Ohmic Resistance Measurement Of Bubble Froth Layer In Water Electrolysis Under Microgravity. *Journal of the Electrochemical Society*. 153(8): 138-143.
- Konrad, T. (2013, November 12). Hydrogen and Fuel Cells Stocks. *Forbes*, Retrieved on January 13, 2014, from <http://www.forbes.com/>.
- Kovacs, K. L., Maroti, G., and Rakhely, G. (2006). A Novel Approach For Biohydrogen Production. *International Journal Hydrogen Energy*. 31:1460–1468.
- Kreuter, W., and Hofmann, H. (1998). Electrolysis: The Important Energy Transformer in a World of Sustainable Energy. *Int. J. Hydrogen Energy*. 23(8): 661-666.
- Krishna, K. M., Md. Mosaddeq-ur-Rahman, Takeshi, M., Tetsuo, S., Kai, Z., and Dongke, Z. (2010). Recent Progress in Alkaline Water Electrolysis for Hydrogen Production and Applications. *Progress in Energy and Combustion Science*. 36(3): 307-326.
- Kumar, S., Saxena, S. K., and Drodz, D. (2012). A Modified Method for Production of Hydrogen from Methane. *International Journal Energy Research*. 36: 1133-1138.
- Kundu, A., Gil, J. H., Jang, J. H., Lee, H. R., Jung, C. R., Ku, B. S., and Chae, K. S. (2010). Room Temperature Hydrogen Production from Water in Auto-Electrolytic Process. . *International Journal of Hydrogen Energy*. 35: 10827-10832.
- Kwak, B. S., Kim J., and Kang, M. (2010). Hydrogen Production From Ethanol Steam Reforming Over Core-Shell Structured Ni_xO_y, Fe_xO_y, and Co_xO_yPd Catalysts. *Int J Hydrogen Energy*. 2010;35: 11829-11843.
- Lin, M. Y., Hourng, L. W., and Kuo, C. W. (2012). The effect of Magnetic Force on Hydrogen Production Efficiency in water Electrolysis. *Int. J. Of Hydrogen Energy*. 37: 1311-1320.
- Lipman, E., and Timothy, E. (2012). Hydrogen Production Science and technology. Robert, A. M. (Ed.) *Encyclopedia of Sustainability and Technology* (pp. 5159-5173). London: SpringerLink.
- Lu, X., Xie, S., Yang, H., Tong, X., and Ji, H. (2014). Photoelectrochemical

- Hydrogen Production from Biomass Derivatives and Water. *Royal Society of Chemistry*. 201443(2014): 7581-7593.
- Maeda, K., Kuramochi, H., Shinkawa, T., and Fukui, K. (2002). Solubility of Two Salts Containing Sulfate and Chloride Ions in Water for Ternary Systems at 313 K. *Journal Chem. Eng. Data*. 47: 1472-1475.
- Maeda, K., Ozaki, N., and Akimoto, I. (2014). Alcohol Additive Effect in Hydrogen Generation from Water with Carbon by Photochemical Reaction. *Japanese Journal of Applied Physics*. 53, 05FZ03.
- Mansouri, K., Ibrik, K., Bensalah, N., and Abdel-Wahab, A. (2011). Anodic Dissolution of Pure Aluminium During Electrocoagulation Process: Influence Of Supporting Electrolyte, Initial pH, and Current Density. *Industrial and Engineering Chemistry Research*. 50 (23); 13362-13372.
- Mark, L. (2015, Jan 28). What is the Greenhouse Effect. *LiveScience*. Retrieved Jan 30, 2015, from <http://www.livescience.com>.
- Mauer, A. E., Kirk, D. W., and Thorpe, S. J. (2007). The Role of Iron In The Prevention Of Nickel Electrode Deactivation In Alkaline Electrolysis. *Electrochim Acta*. 52: 3505-3509.
- Michelle. (2012, August 3). More on Electrolysis. *IGCSE Chemistry*. Retrieved May 12, 2013, from <http://www.askmichellechemistry.blogspot.com>.
- Millan, J., and Klos, K (2013, May 27). Water: Designed for Life, Part 3. *Reasons To Believe*, Retrieved January 11, 2014, from <http://www.reasons.org>.
- Millet, P., Andolfatto, F., and Durand, R. (1996). Design and Performance of a Solid Polymer Electrolyte Water Electrolyser. *International Journal Hydrogen Energy*. 21(2): 87-93.
- Ming, Y. L., and Lih, W. H. (2014). Effects of Magnetic Field and Pulse Potential on Hydrogen Production Via Water Electrolysis. *International Journal Energy Research*. 38(1): 106-116.
- Ming, Y. L., Lih, W. H., and Chan, W. K. (2012). The Effects of Magnetic Force on Hydrogen Production Efficiency in Water Electrolysis. *International Journal of Hydrogen Energy*. 37: 1311-1320.

- Mohamad Aizat b. Abu Bakar (2014). *Enhancement of Closterium Species Hydrogen Production by Laser Irradiation*. Degree of Science, Universiti Teknologi Malaysia.
- Molinari, R., Tiziana, M., and Pietro, A. (2014). Photocatalytic Membrane Reactors for Hydrogen Production From Water. *International Journal of Hydrogen Energy*. 39(14): 7247–7261.
- Nagai, N., Takeuchi, M., Kimura, T., and Oka, T. (2003). Existence of Optimum Space Between Electrodes on Hydrogen production by Water Electrolysis. *Int. J. Of Hydrogen Energy*. 28(1): 35-41.
- Ni, M., Leung, M. K. H., Sumathy, K., and Leung, D. Y. C. (2004). Water Electrolysis A Bridge Between Renewable Resources and Hydrogen. *Proceedings of the International Hydrogen Energy Forum*. 1: 475–480.
- Ni, M., Leung, M. K., Leung, D. Y., and Sumathy, K. (2007). A Review and Recent Developments in Photocatalytic Water Splitting. *Renewable and Sustainable Energy Reviews*. 11 (2007) 401–425.
- Oh, S. E., and Logan, B. E. (2005). Hydrogen and Electricity Production from Food processing. *Water Research*. 39(19): 4673-4682.
- Pan, H. (2014). Metal Dichalcogenides Monolayers: Novel Catalysts for Electrochemical Hydrogen Production. *Scientific Reports*. 5348(4): 1-6.
- Rand, D. A. J., and Dell, R. M. (Eds.) (2008). *Hydrogen Energy: Challenge and Prospects*, RSC Energy. (pp 15-32). Cambridge: RSC Publishing.
- Rangel, C. M., Silva, R. A., Palva, T. I., and Fernandes, V. R. (2009). Solar Hydrogen Production from Aqueous Solutions of Ethanol Near Ambient Temperatures. *International Journal of Hydrogen Energy*. 1-7.
- Riis, T., and Hagen, E. F. (2006). *Hydrogen Production R&D: Priorities and Gaps*. Paris: International Energy Agency IEA.
- Rivin, D., Kendrick, C. E., Gibson, P. W., and Schneider, N. S. (2001). Solubility and Transport Behavior of Water and Alcohols in Nafion. *Polymer*. 42(2): 623-635.
- Robert, M., and Vasilis, F. (2012). Concentrated Photovoltaics. Vasilis, F. (Ed.) *Third Generation Photovoltaics*. (7). USA: OpenIntech.
- Roberto, F. de Souza, Gabriel, L., Janine, C. P., Emilse, M. A. M., Michele, O. de Souza. (2008). Molybdenum Electrodes for Hydrogen Production by Water

- Electrolysis Using Ionic Liquid Electrolytes. *Electrochemistry Communication*. 10(11): 1673-1675.
- Saavedra, R. F., Mancebo, M. B. G., Caravaca, C., Miguel, S., Quejido, A. J., and Alfonso, V. (2014). Hydrogen Production by Two-Step Thermochemical Cycles Based on Commercial Nickel Ferrite: Kinetic and Structural Study *International Journal of Hydrogen Energy*. 39(13): 6819–6826.
- Sarada, S., and Ananthaswamy, J. (1990). Thermodynamic Properties of Electrolyte Solutions: EMF Study of The System $\text{NaCl-Na}_2\text{SO}_4\text{-H}_2\text{O}$ at 25, 35, 45°C. *J. Chem. Soc.* 86(1): 81-84.
- Sasikumar, G., Muthumeenal, A., Pethaiah, S. S., Nachiappan, N., and Balaji, R. (2008). Aqueous Methanol Electrolysis Using Proton Conducting Membrane for Hydrogen Production. *International J. Hydrogen Energy*. 33: 5905-5910.
- Surzycki, R., Cournac, L., Peltier, G., and Rochaix, J. D. (2007). Potential For Hydrogen Production With Inducible Chloroplast Gene Expression In *Chlamydomonas*. *Proceedings of the National Academy of Sciences*. 104(44): 17548–17553.
- Takamura, H. (2002). *Development of High Performance Natural Gas Reforming System for Residential-Use Fuel Cells*. Unpublished note, Japan Science and Technology Corporation CREST.
- Walker, K (2013, Feb 20). What is SynGas? *AzoCleantech*. Retrieved on December 15, 2014, from <http://azotech.com/>
- Wang, H. Z., Leung, D. Y. C., Leung, M. K. H., and Ni, M. (2009). A Review on Hydrogen Production Using Aluminium and Aluminium Alloys. *Renewable and Sustainable Energy Reviews*. 13(4): 845-853.
- Wei, Z. D., Ji, M. B., Chen, S. G., Liu, Y., Sun, C. X., Yin, G. Z., Shen, P. K., and Chan, S. H. (2007). Water Electrolysis on Carbon Electrodes Enhanced by Surfactant. *Electrochimica Acta*. 52: 3323-3329.
- Wendt, H., and Kreysa, G. 1999. *Electrochemical Engineering*. (1st. ed.) Berlin, Heidelberg: Springer-Verlag.
- Winter, J. C., and Nitsch, I. J. (Eds.) (1988). *Hydrogen as an Energy Carrier*. Verlag Berlin Heidelberg. Springer.

- Yacoby, I., Pochekailov, S., Toporik, H., Ghirardi, M. L., King, P. W., and Zhang, S. (2011). Photosynthetic Electron Partitioning Between [Fef_e]-Hydrogenase and Ferredoxin:NADP⁺-Oxidoreductase (FNR) Enzymes In-Vitro. *Proceedings of the National Academy of Sciences*.108(23): 9396–9401.
- Yuvanaj, A. L., and Santhanaraj, D. (2014).A Systematic Study on Electrolytic Production of Hydrogen Gas by Using Graphite as Electrode.*Materials Research*. 17(1): 83-87.
- Zeng, K., and Zhang, D. (2010).Recent Progress in Alkaline Water Electrolysis for Hydrogen Production.*Progress in Energy and Combustion Science*. 36: 307-326.
- Zhao, X., Ong, S., and Kenneth, B. E. (1993).Polarization of Water Molecules at a Charged Interface. Second Harmonic Studies of Charged Monolayers at The Air / Water Interface. *Chemical Physics Letter*.202: 6.
- Zou, Z., Ye, J., Sayama, K., and Arakawa, H. (2001). Direct Splitting of Water Under Visible Light Irradiation With an Oxide Semiconductor Photocatalyst. *Letters to Nature*. 414:625-627.