Development of Spark Electrode for an Explosion Vessel

by

Mizuan Bin Minhat

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

MAY 2011

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Development of Spark Electrode for an Explosion Vessel

By

Mizuan Bin Minhat

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(AP Ir. Dr. Shaharin Anwar Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MIZUAN BIN MINHAT

ABSTRACT

This project is about developing of spark electrode for ignition system by basically using an electrical discharge. A proper set up or assemble for the ignition system need to be done to produce desired spark energy. However, current spark ignition system is not customizing to the research explosion vessel. Further, different spark and explosion propagation are also needed to suite the ignition for the gaseous flammability. Therefore, a suitable ignition system is being created to ensure that energy produced in the spark can be used to study the ignition system for that gaseous flammability. A long electrode holder needs to be design and fabricate to suite the explosion vessel. The orientation for the explosion vessel needs to be understood with the suitable spark gap. According to the working principle of ignition coils, the function is determined and the usage is put as a step up transformer to increase the output voltage. The calculation of the ignition energy is based on discharge capacitor principal. The experiment provides an effective method to produce an ignition spark for a research explosion vessel. Further, the factor that affects the spark size will be determined and the factor will be for the experiment to see the variation of the spark development. The ignition energy can be varied by adjusting the current comes from a power supply. The spark energy should be measureable and highly important in this project is how the safety is conduct to protect against physical or other types or consequences of failure, damage, error, accidents, harm or any other event which could be considered non-desirable. From the finding, the voltage inputs were taken as manipulation factor and the size of the spark were different based on different voltage input. Furthermore, the factor that gives much affect towards the spark size and ignition energy was the capacitance value. Higher capacitance value gives higher ignition energy and further increase the sparks sizes that were produced. Ignition energy and peak pressures vary strongly as a function of initial temperature, but are a weak function of mass loading.

ACKNOWLEDGEMENT

The author would like to express the utmost gratitude and appreciation to Allah because of His blessings along the journey, Alhamdulillah, all praises to Him, even with so much challenges the Final Year Project managed to be completed on time.

Without the utmost support and assistance from the Mechanical Engineering Department of Universiti Teknologi PETRONAS in providing excellent support in terms of academic, knowledge and moral motivation, it is fair enough to say that this project would be impossible to be completed. The author would like to express his sincere appreciation to the project supervisor, AP Ir. Dr. Shaharin Anwar Sulaiman for his continuous support and guidance throughout the challenging journey of completing the project. His valuable guidance and the most important thing is, he is like a father figure for the author and always be the place to ask for some motivations and critics. Other than that, special thanks to Ms Salina Mohmad the Electrical and Electronic department's lecturer who contributed in giving an idea and help in completing this project.

The author will always have the soft spot for the technical staff especially those from Energy Department who are involved with this project, namely Mr. Khairul and Mr Fahmi, who helped the author the most in order to understanding the technical use of all the equipment. The authors hope that the outcome of this report will bring beneficial output to others as well.

Furthermore, I would like to express my appreciation towards my sponsorship which is Petroliam Nasional Berhad (PETRONAS) for giving me opportunity to study in this university and sponsoring all my financial in studying and also in completing this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

CHAPTER 1
INTRODUCTION

1.1 Project Background

A spark electrode is an electrical device that fits into the cylinder head of some internal combustion engines and ignites compressed fuels such as aerosol, gasoline, ethanol, and liquefied petroleum gas by means of an electric spark. Normal spark electrode have an insulated central electrode which is connected by a heavily insulated wire to an ignition coil or magneto circuit on the outside, forming, with a grounded terminal on the base of the electrode, a spark gap inside the cylinder. This project is based on the normal spark electrode but some modification will be done to ensure that the electrode wills suite the vessel perfectly. Moreover, the spark electrode will be charge by electrical discharge with proper ignition system to produce energy for the spark.

An explosion is often identified by a loud noise, or "bang" resulting from the sudden release of energy. A more precise definition in the context (Eckhoff, 2005) is to define an explosion as an exothermal chemical process that, when occurring at constant volume, gives rise to a sudden and significant pressure rise. Explosions in the process industries include gas, spray/mist and dust explosions. These three categories of chemical explosions have similar ignition and combustion properties.

The spark size that will be determined based on the ignition energy and other several factors to obtain suitable ignition energy for a certain gases. In other side, the variation of the spark will be taking into consideration to see the development of the spark and to determine the time of ignition to completely ignite the combustion or explosion.

1.2 Problem Statement

Most gas explosions happen when combustible gases were releases, mix with air in the atmosphere and generate an explosive cloud. If the fuel/air ratio in the cloud is within the flammability limits, and there is a presence of an ignition source, an explosion will occur. Therefore, a reliable ignition source or system is needed to support the explosion vessel to study the flow propagation. Somehow, present ignition system is not customizing to the research of the explosion vessel. It is because of the spark energy can not be determined, the spark electrode is not suitable with the explosion vessel and some of the parameter such as temperature, pressure, input voltage and others will give an affect towards the ignition of the explosion. Furthermore, the spark and the variation needed for this experiment are different from the current system. This project also is trying to counter basic ignition problem which is lack of spark and lack of gasoline. Here, a suitable spark size of the ignition system will help to create a perfect ignition for the combustion or explosion. Minimum ignition energy will give the answer where minimum ignition energy for those gaseous can also be determined. One of the best ignition systems is using the spark electrode because with the right assemblies for gas ignition systems, it can incorporate flame sensor rods, spark ignition systems and a combination of both in a variety of sizes and configurations that can be suite inside the explosion vessel. Here, the spark energy required for the certain gaseous can be determined so that the explosion or flammability can perfectly be produced.

1.3 Objective

The objective of this project is to develop a single spark electrode system for gaseous mixture in a research explosion vessel. A spark electrode assembly for gas range igniter system is disclosed which is low cost and reliable in operation. Reliable in operation can be explained as the ignition system should be developing with proper parameter whether it related to the equipment set up or the environment such as affect of pressure or temperature. In this project also, it also need a proper design for the spark electrode to be suite in the explosion vessel. A certain parameter will be set to determine the ignition energy for those fuel mixtures and counter basic ignition problem which is lack of spark and lack of gasoline. The spark that been produced is based on jump spark type. Jump sparks are caused by the release of electrical energy stored on a capacitor across a spark gap. The capacitor energy is in electrostatic form and the spark occurs when the voltage of the spark gap reaches the breakdown voltage. The spark size will be determined to investigate a suitable ignition for the gases.

1.4 Scope of Work

The scope of study is regarding energy measurement for the ignition system. Other than that is finding the suitable parameters for the electrode design to suite the explosion vessel. The actual data for those fuel mixtures ignition energy will be gathered before it will be tested to prove it. The development of the electrode also will take part of design parameters and fabrication lab to fabricate the electrode with the proper design constraint to suite the explosion vessel. The assemblies of the ignition system circuit needs a guide from electrical department and the full assembly for all the apparatus including the high speed camera, power supply, timer and etc will be done in mechanical lab. The research need to be done in minimum ignition energy, spark electrode design, electrical ignition system circuit for the igniter, used of high speed camera to measure the spark duration and some other parameters to measure the spark energy. The perfect range where the ignition energy needed will be determined and the variation of the spark size that will affect the ignition will be examined based on manipulation of several factors.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Spark System

Spark is defined as discontinuous electrical discharges across a gap between at least two electrodes constituting the analytical gap (spark gap). The discharge current is supplied by a cyclically charged capacitor, C. The spark ignition voltage across the analytical gap drops from the initial capacitor voltage, U_{cap}, to the low burning voltage, U_b, of an arc within a time that is short compared to the spark duration. Therefore, basically, sparks can be considered as interrupted arcs of higher initial current, I_o or peak current and of a lower duty cycle.

The spark capacitor C is charged through the charging circuit, a rectifier, a charging resistor and electronic or other devices for the control of charging current, peak capacitor voltage, U_{cap}, and the phase. If the capacitor is always charged at the same polarity, a dc spark will result and in the case of an alternating charging voltage, an ac spark. The discharge circuit connects the capacitor of capacitance C with the analytical gap. It may contain inductors, of induction L, a resistor of resistance R, and devices for triggering the spark for control and synchronization purposes for example control spark gap (IUPAC, 2007).

2.2 Spark Discharge and Electrode Issues

Previous studies on spark ignition have shown that there is variability in results due to the dependence of ignition energy on the electrode construction and discharge circuit design. Quantifying the strength of a short-duration, low-energy capacitive spark ignition source has been found to be difficult (Strid, 1973); thus a standard for spark energy has not been developed. The ASTM ignition energy test (ASTM, 1988) follows the practice started by (Lewis et al, 1961) of reporting the stored energy rather than measuring the energy discharged into the spark. Some test procedures require flanges to be used on electrodes (ASTM, 1988), while other researchers (Crouch, 1994) do not use flanges and find comparable ignition energies to studies done with flanges.

In the present study, it is reported the "energy stored" as the ignition energy and used unflanged electrodes. Some of the issues connected with these choices are explored in the next two sections. Ultimately, the validation of these choices and experimental protocol was confirmed by doing control experiments with propane and hexane. The values of ignition energy compare favorably with those of previous researchers for the overlapping ranges near the minimum ignition energy, and interpolate smoothly between the lean limit and the minimum ignition energy values.

2.3 Minimum Ignition Energy Theory

There are two basic theories of ignition process by electric sparks. The electrical model considers transport of chemical energy by the internal diffusion of reactants and reaction products while the thermal model considers the transport of the thermal energy i.e. heat. Even while no complete ignition theory was available, (Strid, 1973) concluded that the hypothesis of thermal ignition seemed to be supported by the experimental minimum ignition energy determination. A recent overview of ignition theories is given by (Babrauskas, 2003).

According to the thermal theory of electric spark ignition of (Lewis et al, 1961), the spark establishes instantly a small volume of hot gas immediately after the discharge. At first the temperature within this flame kernel increases rapidly, but as the ignition volume grows in size, the temperature decreases due to the flow of heat to the ambient unburned gas. In the adjacent layer of ambient gas the temperature rises and induces chemical reactions, so that a combustion wave is formed and propagates outwards. At the time that the temperature within the flame kernel has decreased to the order of normal flame temperature, the diameter of the flame kernel must have grown to a certain size for self-sustained combustion, i.e. ignition, to be established. The flame kernel has more or less a spherical shape. If the size is too small, the heat loss to the three unburned gases continuously exceeds the heat gain by chemical reaction, so that the reaction will gradually cease, leading to the extinction of the combustion wave (after only a small amount of gas around the original spark has burned). The minimum ignition energy is the energy required to establish the flame kernel of the minimum critical size for subsequent self-sustained flame propagation. Figure 2.1 shows an overview of the energy balance for electric spark discharge based on the thermal theory.

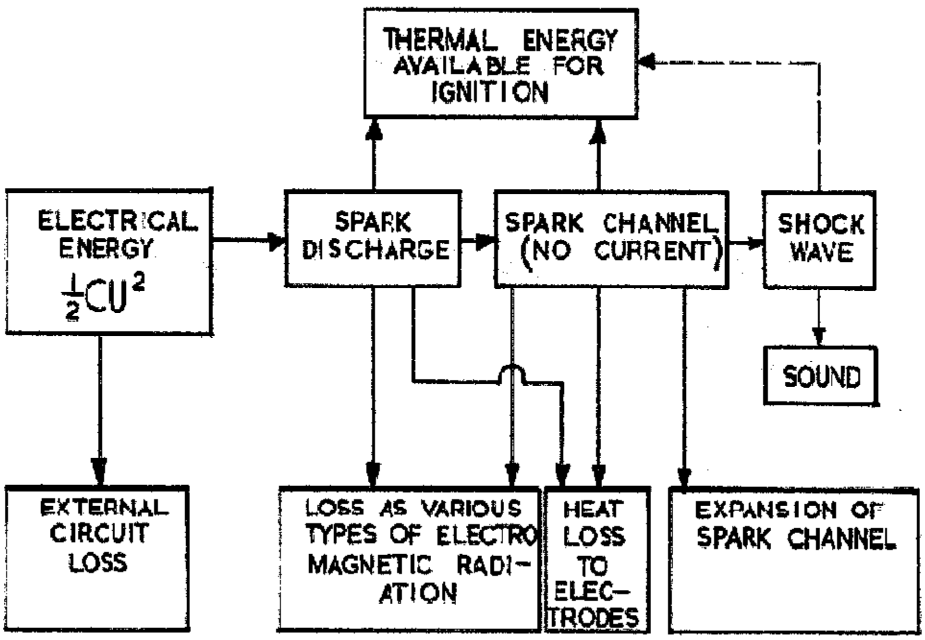


Figure 2.1: Energy balance of an electric spark discharge based on the heat (thermal) theory (Eckhoff, 1970)

2.4 Electrical Theory of Electrical Spark Ignition System

The electrical theory of electrical spark ignition supposes that the electrical discharge activates the chemical reaction by producing free radicals/ions in the discharge zone, which diffuse into the surrounding gas and initiate a self-propagating combustion chain. Therefore the ignition conditions of the mixture are dependent on the concentration of the reactive particles. In practice, accidental electrical spark discharges are usually of capacitive nature i.e. electrostatic discharges. The discharges were divides which have caused accidental ignitions into six different categories which are; corona, brush, powder heap, sparks, propagating brush and lightning-like discharge (Babrauskas, 2003). In the present work, only spark discharges are used as ignition source.

2.5 Spark Discharge Features that may Influence Spark Incendivity

The establishment of a self-sustained flame front in the combustible gas mixture is strongly influenced by the discharge mode and the geometry of the plasma volume, generated by the spark discharge. The total energy involved plays only a minor role. The spark discharge process had been divided in three main phases: breakdown, arc and glow phases (Maly et al, 1978). Any spark ignition system includes a different combination of these three discharge modes, with varying energy content and durations depending on the discharge circuit. Figure 2.2 shows both gap voltage and current vary as functions of time during a spark discharge.

With very short spark durations of the order of 10^{-9} s (1 ns) more than 80 % of the energy is transformed into plasma during the breakdown phase. The arc and glow phases last much longer and their energy transfer efficiencies are much less.

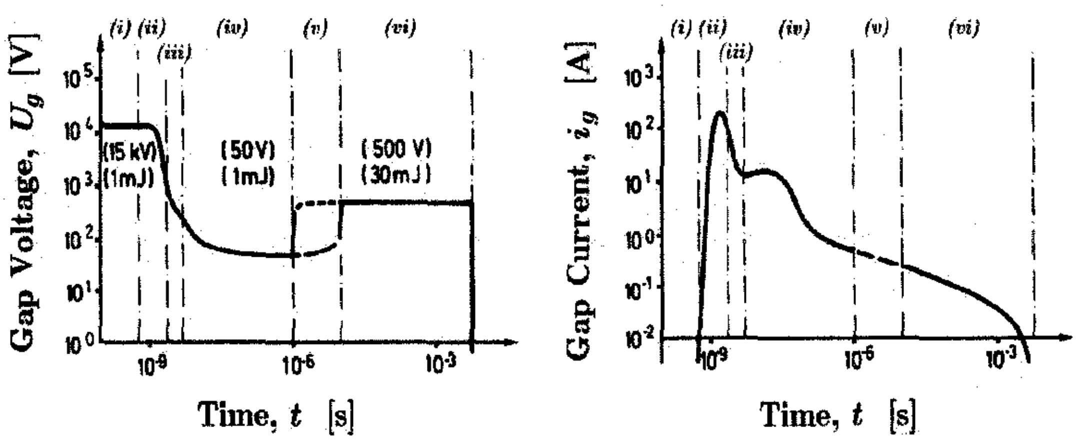


Figure 2.2: Schematic diagram of voltage and current vs. time in a spark discharge of a typical spark ignition system. The six discharge phases are: i) pre-discharge, ii) breakdown, iii) breakdown/arc transition, iv) arc v) arc/glow transition, and vi) glow (Maly et al, 1978)

2.6 Working Principle of Ignition Coil

Ignition coils are the execution units of a vehicle ignition system, which provide ignition energy to ignite air-fuel mixture in the chamber of the engine (Omar, 2007). In the working process of the coils, primary coils and secondary coils repeatedly store and release energy according to various rotational speed of the engine. The working principle is shown in Figure 2.3. The ignition process can be divided into three stages. First, ignition signal generated by embedded control unit (ECU) breaks the Darlington transistor over to make L1 store energy, and a magnetic field is gradually enhanced accompanied with the increasing of the primary coils current. Then, Darlington transistor is cut off, and the rapid attenuation of the magnetic field intensity induces a high voltage in secondary coils. Finally, the voltage breaks down the spark plugs, and the mixture is ignited.

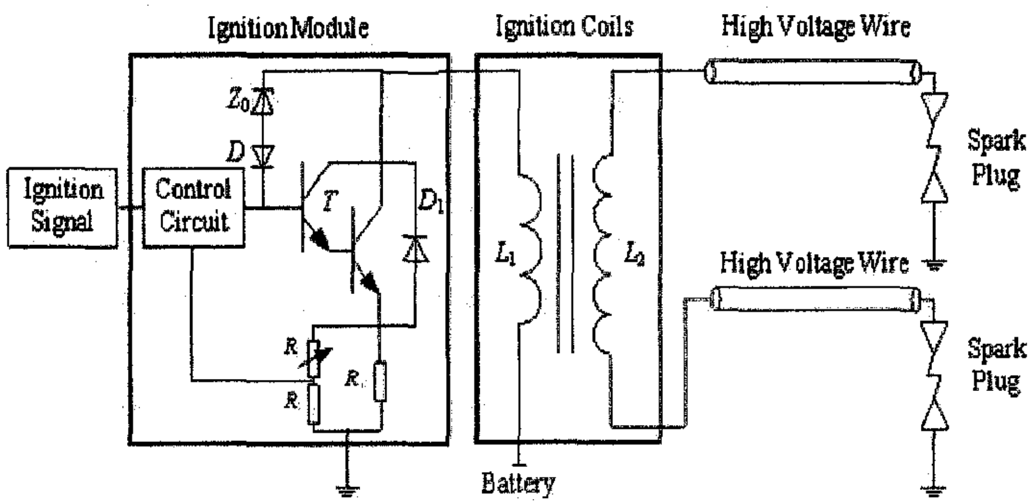


Figure 2.3: Working principle of ignition coils (Omar, 2007)

2.7 Effects of Spark Energy to a Spark Kernel

The data obtained with the measured kernel radius, breakdown energy, and spark energy curve for the case of the 2.0 mJ spark. Shown in Figure 2.4 is the prediction of the flame kernel growth pattern with the discharge data from the 11.5 and 54.8 mJ sparks. A qualitative agreement is achieved in both cases. The trend of increasing kernel size with additional spark energy is adequately predicted. Although the prediction is slightly lower during the first 600 μs for the spark of 11.5 mJ and a little higher after 800 μs for the case of 54.8 mJ, the overall agreement is within the statistical variation of the data. It is interesting to note that the kernel sizes for all the cases in Figure 2.4 are adequately correlated with a single value for the constant C despite the apparently different slopes of the experimental curves (Lim, 1987).

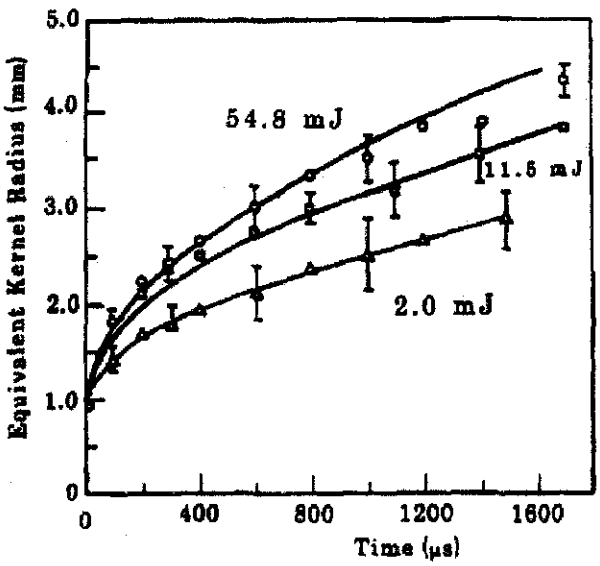


Figure 2.4: Comparison of predicted (solid lines) and measured flame kernel radii for different spark energies at I= 0.7. Experimental data points are reproduced (Lim, 1985)

The average kernel temperatures from the model predictions are plotted in Figure 2.4. The results indicate that increasing the spark energy raises the kernel temperature in addition to creating a larger kernel size through more mass entrainment (Lim, 1987). This higher temperature for a more energetic spark increases its expansion speed relative to that of a less energetic spark even though the burning speeds are identical.

When a nearly minimum amount of ignition energy (2.0 mJ) is released, the kernel temperature drops monotonically toward the adiabatic flame temperature of the mixture. An excess amount of spark energy over the minimum (11.5, 54.8 mJ), however, initially raises the average temperature to a peak value, before decreasing again toward the adiabatic flame temperature. From a practical viewpoint, the hotter and larger flame kernel of an energetic spark will be less vulnerable to possible quenching under unfavorable circumstances. Such conditions can be manifested by a large metal surface near the spark gap, a small spark gap distance, and a high level of mixture motion.

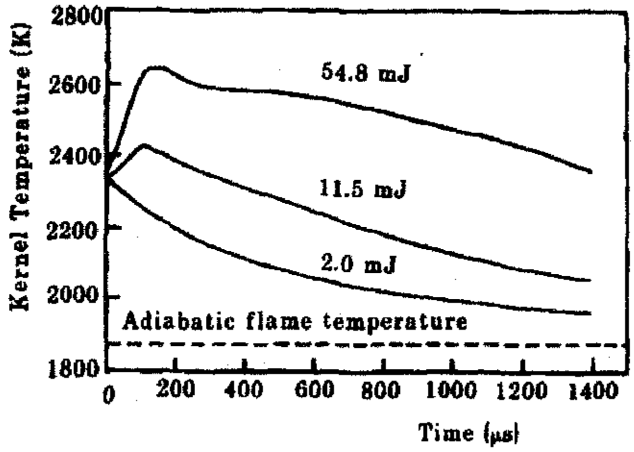


Figure 2.5: Predicted kernel temperature for spark of Figure 2.4 (Anderson, 1987)

Figure 2.6 shows that the fraction of the total energy in the kernel produced by the spark discharge generally decreases in time as one would expect. The percentage varies considerably in the time frame shown and depends upon the spark energy input. For the 54.8 mJ spark, more than 25 % of the energy in the kernel is due to the spark after 1 ms, while it is only about 10 % or below in the other two cases.

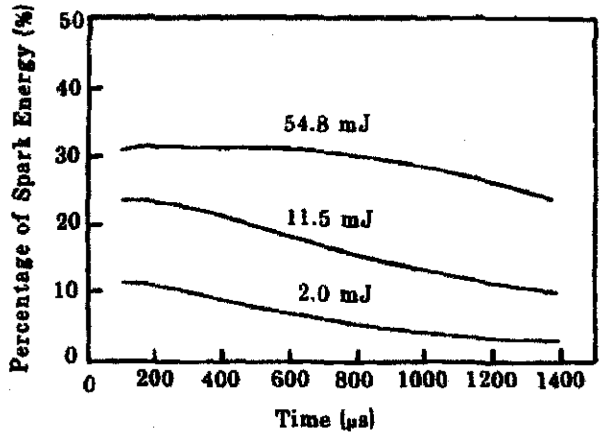


Figure 2.6: Contribution of the spark to the total energy in the kernel for sparks of Figure 2.4 (Anderson, 1987)

2.8 Spark Ignition

One potential source of ignition in accidental fires and explosions is an electrical discharge or spark. Other possible sources include hot surfaces or adiabatic compression of fuel-air mixtures. The origin and characterization of common ignition sources are discussed at some length parameter in the standard literature on fire and explosions (Kuchta, 1985). In the present study, the experiment was aim concentrated on capacitive spark discharges as a means for characterizing the potential for ignition of electrical discharges.

Following (Magison, 1978), it is convenient to categorize electrical ignition modes as sparks created across a fixed or closing gap by energy stored in a capacitive circuit, arcs created across an opening circuit by energy stored in an inductor, opening or closing contacts in a purely resistive circuit, Hot metal wires, particles, or surfaces created by ohmic heating of a circuit element, such as a wire strand.

All of these possibilities have been examined extensively in the context of explosion hazard prevention (Magison 1978), but the most often studied has been the capacitive spark. The standard way to characterize capacitive discharge sparks is in terms of the quantity of stored electrical energy, measured by the mili Joule (mJ). The actual amount of energy that is deposited in the gas by the discharge is lower but difficult to quantify, particular for short duration sparks.

This issue is considered in more detail in the discussion section. It is found that for mixtures of a given fuel with an oxidizer such as air, there is a minimum spark energy required to cause ignition when the mixture falls in the range of flammable compositions. In this report, this energy will be simply referred to as the ignition energy.

Beginning with the work of Guest at the Bureau of Mines in the 1940s and continued by (Blanc, 1947), an extensive series of tests (Lewis et al, 1961) was carried out to determine ignition energy in hydrocarbon-air vapors. Ignition energy was found to be a function of fuel type and composition. For a given fuel, the ignition energy is a U-shaped function of composition with the vertical portions of the "U" occurring at the flammability limits and bottom of the "U" at some intermediate composition as shown in Figure 2.7. The ignition energy for the most sensitive mixture is known as the Minimum Ignition Energy. For both leaner and richer mixtures, the ignition energy increases sharply from the minimum ignition energy. The minimum ignition energy for hydrocarbon fuels in air has been measured and determined for many common substances (Lewis et al, 1961) and is known to be on the order of 0.2 mJ and usually occurs for a rich composition. Examples of measured minimum ignition energy that stated by (Lewis et al, 1961) is shown in Figure 2.7. Based on these results, the minimum ignition energy for all petroleum-based fuels, including aviation kerosene is assumed to be on the order of 0.2 mJ.

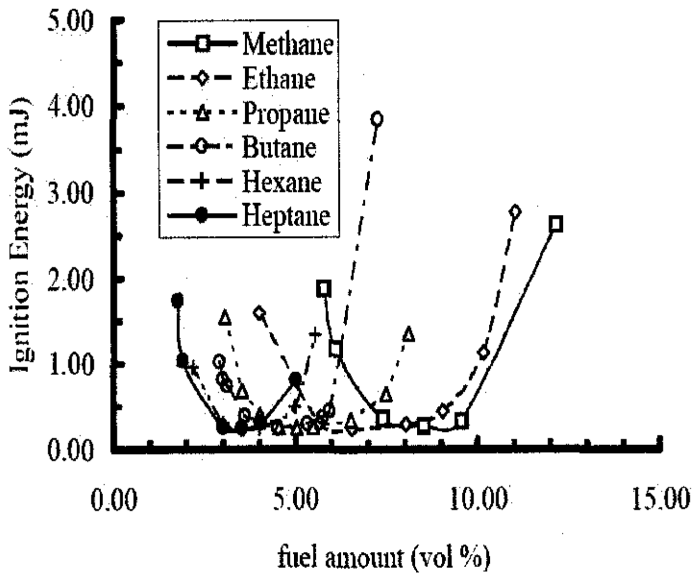


Figure 2.7: Classical results on ignition energy by (Lewis et al, 1961)

CHAPTER 3
METHODOLOGY

3.1 Overall Project Flow

The Incremental and Iterative methodology (Basili, 2003) is chosen for this project. Development of the project will be based on several phases all of which will be visited sequentially, and then revisited as required to suit the changes and requirements of the project. Each revisit will be done according to the needs of the project. Once satisfying all the conditions, the development is halted. This methodology is chosen as a means to adapt to changes found during the development of the project, such as a new requirement or a time constraint.

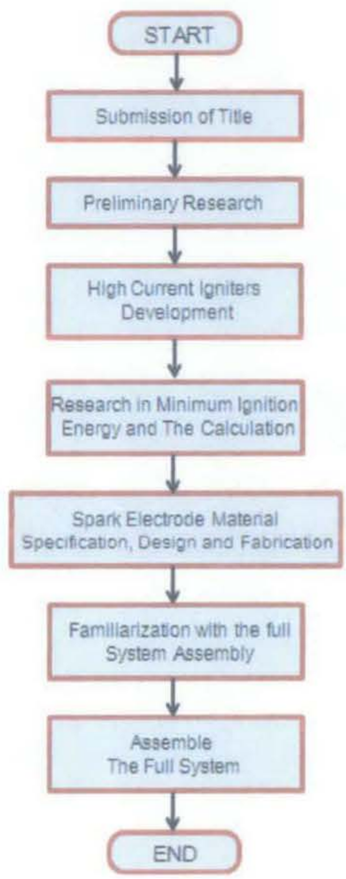


Figure 3.1: Project methodology

The methodology starts with selection of the title given by the lecturer. After some of research for a few title in hand, finally the author decide to take the project title which is Development of Spark Electrode for An Explosion Vessel. Next, the author start to make an overall research related to the topic. The research is regarding journal, experiment and conclusion made by some of qualified researcher that related to this topic. The aim for this first step research is to find the objective, problem statement, introduction and the basic information about ignition energy and developing a spark. After those research is done, the preliminary report need to be submitted.

High current igniter contains a circuit that will create the ignition system. The circuit should contain a power supply, resistor, capacitor, transformer and other electrical equipment to operate develop a spark at the spark gap between the electrodes. At the spark gap, the energy produce must be measurable so that all the equipment used can be arranged due to its function to obtain desired energy for the spark. Then, research in minimum ignition energy will be done. Minimum ignition energy is the minimum amount of energy required to ignite a combustible vapor, gas or dust cloud, for example due to an electrostatic discharge. Different fuel mixture surely will have different minimum ignition energy and it is affected by temperature, pressure, spark gap and others. By knowing the minimum ignition energy for those fuel mixtures which is propane and iso-octane, development of the circuit can be done correctly.

Then, we enter the toughest work which is designing the spark electrode. The spark electrode must suite the explosion vessel tightly and the igniter must be at the center of the vessel. The spark gap also will give different amount of power required for the ignition. Therefore, lots of test and calculation need to be done to ensure the spark electrode can use perfectly in the cycle. In the schematic of the control circuit for the ignition system, there are lots of equipments need to be assembled. The equipments are principal trigger switch, digital camera, power supply, high current igniter and others. Therefore, familiarization and better understanding with all those equipment will surely create a better condition in doing the experiment. Lastly, all the equipment will start being assembled and the test will be done to test the ignition energy required for that fuel gaseous mixtures.

No.	Activities/Work	1	2	3	4	5	6	MID-SEMESTER BREAK	7	8	9	10	11	12	13	14
1	Selection of project title															
2	Preliminary research work Research about ignition energy															
3	High Current Igniter Circuit Development with Calculation															
4	Researches and literature review															
5	Research about Minimum Ignition Energy (MIE) and calculation involve															
6	Spark Electrode material specification															
7	Design the Spark Electrode															
8	Familiarization with circuit for ignition, camera and laser system															
9	Experimental work and Assemble of the system															
10	Submission of Preliminary Report				●											
11	Submission of Progress Report									●						
12	Seminar									●						
13	Submission of Interim Report Final Draft															●
14	Oral Presentation								During Study Week							

● Suggestion Milestone

Process

Process Done

Figure 3.2: Project activities and milestones for FYP I

No.	Activities/Work	1	2	3	4	5	6		7	8	9	10	11	12	13	14
1	High Current Igniter development							MID-SEMESTER BREAK								
2	Equipment preparation															
3	Spark Electrode material specification															
4	Spark Electrode fabrication															
5	Full ignition system assemble															
6	Experimental work															
7	Minimum Ignition Energy calculation															
8	Poster preparation															
9	Final project wrap up															
10	Submisson of Progress Report I								●							
12	Seminar											●				
13	Poster Exhibition												●			
14	Submission of Dissertation Final Draft															●
15	Oral Presentation								During Study Week							
16	Submission of Dissertation (Hard Bound)								7 day after oral presentation							

● Suggestion Milestone
Process
Process Done

Figure 3.3: Project activities and milestone for FYP II

3.2 Schematic of the Complete Control Circuit

In Figure 3.4 is the full assembly of the ignition system. It contains the power supply, ignition system, high speed camera, signal converter and other component. Signal converter used to convert signal from plug to both opto-isolator and pulse receiver. Opto-isolator will produce enough light to support the high speed camera to capture the spark image much clearer. The important part is the ignition system part which label in the dash line box. The detail of ignition system is shown in High Current Igniter / Switching Circuit paragraph later. Main function of the ignition system is to develop the spark by the spark electrode. The digital camera will be used to capture the spark and calculation of the ignition energy that been produced will be done by PASCO device which is a signal converter together with a computer.

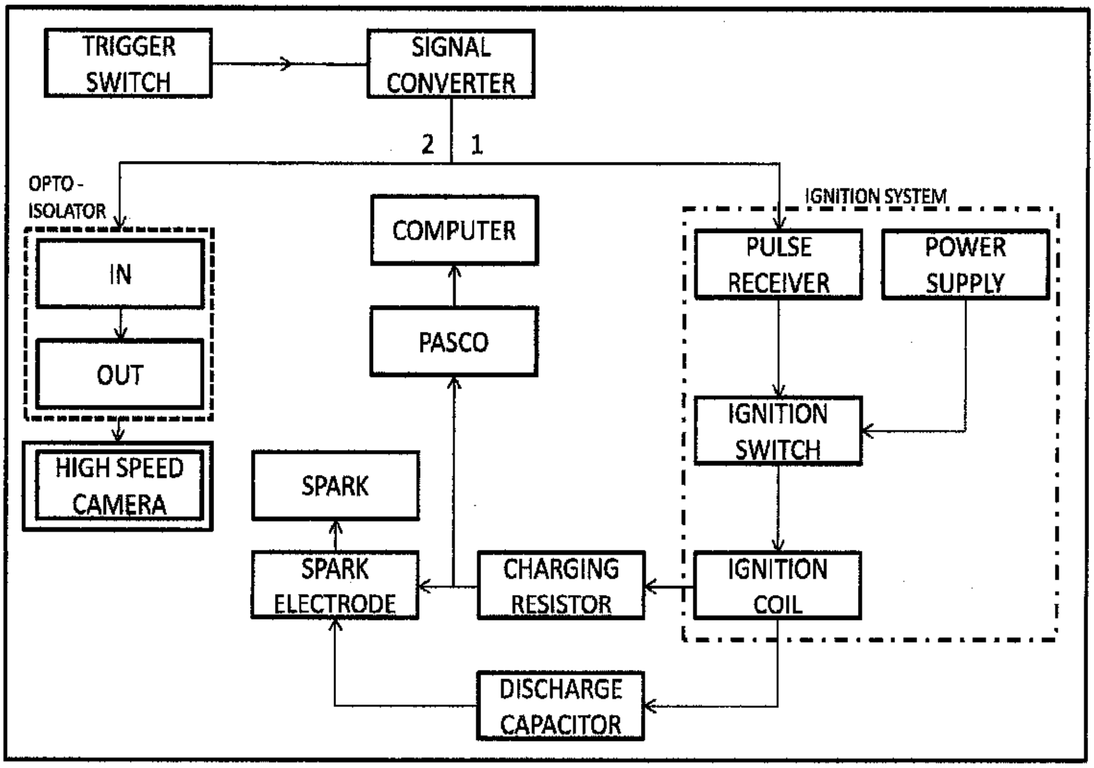


Figure 3.4: Schematic of control circuit for ignition system and high speed camera

3.3 Details of Ignition System

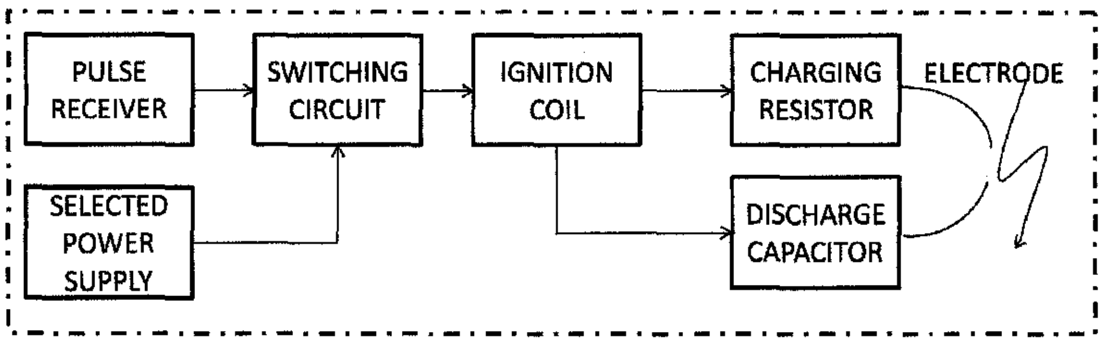


Figure 3.5: Schematic of the ignition system

Ignition system shown in Figure 3.5 contains full equipment for the ignition system. It starts from power supply that produces DC current for the flow. A power supply is a device that supplies electrical energy to one or more electric loads. The term is most commonly applied to devices that convert one form of electrical energy to another. A regulated power supply is one that controls the output voltage or current to a specific value; the controlled value is held nearly constant despite variations in either load current or the voltage supplied by the power supply's energy source. The model of power supply that being used for this experiment is INSTEK GPS-3030DD. The voltage can be varied from 0 V to 32 V with current 0 A to 3 A. However, one unit of that model of power supply is not enough to produce the power to discharge the spark. Therefore, two same model of the power supply has been put in series to give much higher current to give extra power to the ignition system. As a result, the total voltage that can be varied is from 0 V to 64 V with current from 0 A to 6 A. Direct current (DC) is produced, it is refer to power systems that use only one polarity of voltage or current, and to refer to the constant, zero-frequency, or slowly varying local mean value of a voltage or current. For example, the voltage across a DC voltage source is constant as is the current through a DC current source. The DC solution of an electric circuit is the solution where all voltages and currents are constant. It can be shown that any stationary voltage or current waveform can be decomposed into a sum of a DC component and a zero-mean time-varying component; the DC component is defined to be the expected value or the average value of the voltage or current over all time.

The spark gap initially appears as an open-circuit. Current from the HV power supply flows through a ballast inductor and charges the primary tank capacitor to a high voltage. The voltage across the capacitor increases steadily with time as more charge is being stored across its dielectric. Eventually the capacitor voltage becomes so high that the air in the spark gap is unable to hold-off the high electric field and breakdown occurs. The resistance of the air in the spark gap drops dramatically and the spark gap becomes a good conductor. The tank capacitor is now connected across the primary winding through the spark gap. Energy is stored alternately as voltage across the capacitor or current through the capacitor. Some of the energy from the capacitor also produces considerable heat and light in the spark gap. Energy dissipated in the spark gap is energy which is lost from the primary tank circuit, and it is the energy loss which decays relatively quickly with time.

3.4 High Current Igniter Circuit / Switching Circuit

Switching circuit is a high current igniter circuit. It contains several electrical components that combined to produce an electrical discharge to the ignition coil. The ignition switch enables the operator to turn the ignition on and release the spark at the spark electrode.

Voltage Supply = 0 – 60 V

Voltage Input before timer (example: 5 V)

Timer Resistance = 50 Ω

$$V = IR$$

$$I = \frac{5\ V}{50\ \Omega}$$

$$= 0.1\ A$$

Capacitor (in parallel)

$$C = 5.6\ \mu F + 5.6\ \mu F$$

$$= 11.2\ \mu F$$

Resistor (in parallel)

$$\frac{1}{R} = \frac{1}{12\ k\Omega} + \frac{1}{2.2\ k\Omega}$$

$$R = 1.86\ k\Omega$$

Impedance

$$Z = \text{sqrt}(R^2 + C^2)$$

$$= \text{sqrt}(1.86\ k\Omega^2 + 11.2\ \mu F^2)$$

$$= 0.033\ k\Omega$$

Output Voltage

$$E = IZ$$

$$= (0.1\ A) \times (0.033\ k\Omega)$$

$$= 3.3\ V$$

From the circuit calculation, the current produce into the timer are varied by the input voltage. With a constant resistance through the timer, the current will increase as the voltage input is increase. The circuit output voltage will be depending on current from timer and as the current increase, the voltage will increase. However, the voltage output is lower than input voltage due to some voltage drop across the component resistance.

3.5 Ignition Coil (Flyback Transformer)

An ignition coil is essentially an autotransformer with a high ratio of secondary to primary windings. By "Autotransformer", the primary and secondary windings are not actually separated, they share a few of the windings.

A flyback transformer (FBT), also called a line output transformer (LOPT), is a special transformer which used for conversion of energy (current and voltage) in electronic circuits. It was initially designed to generated high current saw tooth signals at a relatively high frequency. In modern applications it used in switched-mode power supplies for both low (3 V) and high voltage (over 10 kV) supplies.

When the switching transistor is turn on in a fly-back converter, the primary winding of the transformer is energized, and no energy is transferred to the secondary windings. When the transistor is turned off the field collapses and the energy is transferred to the secondary windings. This differs from a forward converter topology, where energy is transferred to the secondary windings when the switching transistor is turned on. The difference between the two topologies can be seen by looking at the orientation of the dots on the secondary compared to the primary. For the fly-back converter, the dot's are reversed, and for the forward converter the dots are aligned.

The primary winding of flyback transformer is driven by a switch from a DC supply (usually a transistor). When the switch is switched on, the primary inductance causes the current to build up in ramp. When the switches are turned off, the current in the primary winding collapse leaving the energy stored in magnetic core. The voltage in the output winding rises very quickly (usually less than a microsecond) until it is limited by the load conditions. Once the voltage reaches such level as to allow the secondary current to flow, then the current in the secondary winding begins to flow in a form of a descending ramp (Dixon, 2001).

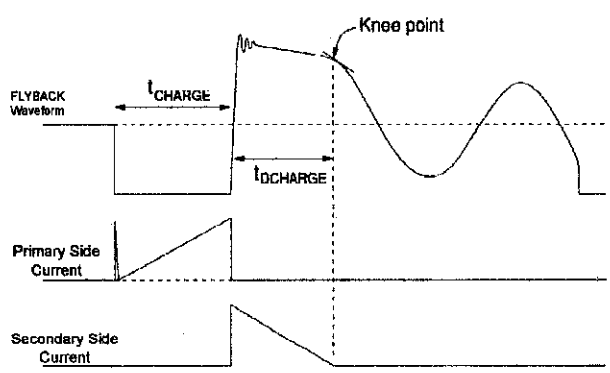


Figure 3.6: Current waveforms in a flyback transformer (Dixon, 2001)

3.6 Energy Calculation

Voltage is a representation of the electric potential energy per unit charge. Voltage is a scalar quantity. The SI unit of voltage is the volt, which is can also be defined as 1 Volt = 1 joule/coulomb. Electrical current is a measure of the amount of electrical charge transferred per unit time. It represents the flow of electrons through a conductive material. Current is a scalar quantity and the SI unit of electrical current is the ampere, defined as 1 coulomb/second.

Capacitor is a component that is used to store an electrical charge and is used in timer circuits. A capacitor is used with a resistor to produce a timer. Sometimes capacitor is used to smooth a current in a circuit as they can prevent false triggering of other component such as relay. When power is applied to a circuit that contains a capacitor, the capacitor will be charges up. Once the power is turned off, the capacitor discharges its electrical charge slowly.

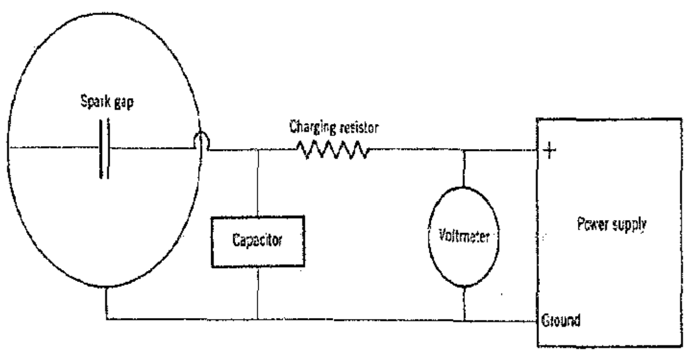


Figure 3.7: Block diagram of the electric spark circuit of ASTM for determination of minimum ignition energy for gases and vapours (Litchfield, 1967)

A spark discharge circuit was constructed based on the circuit of the ASTM. Figure 3.7 shows a high-voltage power supply connected to charging a 33 K'Ω, 5 W resistor. A capacitor was connected directly across the spark gap and the charging resistor was connected in series from the power supply.

After the gas mixture of the desired concentration has been loaded into the explosion vessel, the applied voltage across the spark gap was increased gradually until a sparks occurred. Some introduction experiments were performed with the aim to find the spark breakdown voltage in air for 2.0 mm spark gap length. According to (Babrauskas, 2003), for a spark gap distance of 2.0 mm the breakdown voltage is around

6.0 kV. Due to the statistical nature of spark discharges, the breakdown occurs at different voltages even for apparently identical test conditions. The spark energy E was calculated by:

$$E = \frac{1}{2} CU^2 \tag{3.1}$$

where C is the energy storage capacitance, the sum of the capacitance of the electrode gap and the stray capacitance. U is the spark voltage at the moment of discharge. C and U have the standard units of F (Farad) and V (Volt).

The capacitor value was manipulated to obtain a different energy value that produced at the spark gap. There are 4 types of capacitor value that are being used to vary the energy value. However the high peak voltage that being produced from the flyback transformer is difficult to measure because there is no electrical equipment from the laboratory that can be used to measure that high voltage. Therefore, Paschen's Law theory was being implemented to estimate the value of the peak voltage. Paschen found that the air breakdown voltage was described by:

$$V = \frac{a(pd)}{\ln(pd) + b} \tag{3.2}$$

where V is the breakdown voltage in volts, p is the pressure in atmospheres in bar, d is the gap distance in meters. The constant a and b depend upon the composition of the gas. For air at standard atmospheric pressure, a = 43.6 x 10^6 V/(atm.m) and b = 12.8.

At first, the gap for the electrode was set to certain value usually from 0.5 mm onwards until no spark can occur. Then current from the power supply is varied start from 3.5 A to 4.5 A and a voltage maintained at 12 V. Once there is no spark that occurs for example at the length of 3 mm, the value will be added to Equation 3.2 (Paschen's Law) to estimate the value of spark discharge based on the supply power from the power supply. Then, the voltage value will be added to Equation 3.1 together with discharge capacitor value to estimate the energy that been produced by theoretical calculation.

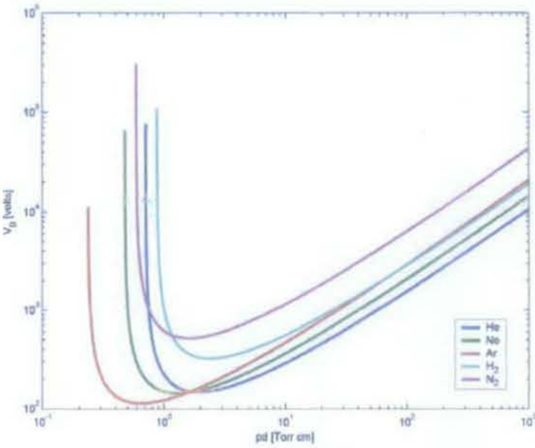


Figure 3.8: Paschen Curve using the expression for the breakdown voltage as function of parameters A and B (Paschen, 1889)

In this experiment, four type of capacitor has been test to see the different in spark size, variation of spark size due to energy variation and ignition of the explosion by the spark. Those capacitors have been name to make it much easier to recognize and the detail can be seen in Table 3.1.

Table 3.1: Capacitor type

	Capacitor Name	Capacitance Value	Voltage
i	Box Blue	6.8 pF	2kV
ii	Flat Blue	4.72 pF	2kV
iii.	Big Blue	1.0 pF	2kV
iv	Big Brown	1.0 pF	1.6kV

3.7 Electrode Design

The electrode designs contain three main parts which are the center electrode, ground electrode and insulator. The main objective of the design specification is to suite the explosion vessel and therefore, at first the design is created based on the size of the explosion vessel. After the design will complete, the electrode will be test by Digital Multi Function Tester to check any leakage through the insulator and weather the design meet the basic standard to deliver the spark in safe.

Explosion Vessel

Inside Diameter: 320mm

Outside Diameter: 410mm

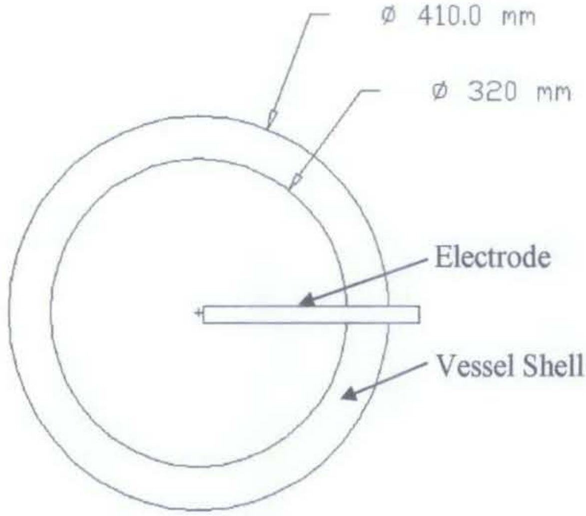


Figure 3.9: Sketch of the explosion vessel

Therefore, length of electrode:

a) Ground Electrode

Radius or $L_{min} = \frac{410mm}{2} = 205mm$

Suitable L = 205 + 25mm

= 230mm

b) Insulator

Suitable L = 205mm + 35mm (to cover whole Ground Electrode surface)

= 240mm

c) Center Electrode

Suitable L = 205mm + 45mm (extra length to connect to high tension cable)

= 250mm

From the above calculations, those measurements were taken in designing the full electrode design that will be fabricated later on. However during fabrication, some of the parameters such as diameter were change a little bit to ensure they are fit perfectly.

Figure 3.10: Ground electrode design detail

Figure 3.11: Insulator design detail

Figure 3.12: Center electrode design detail

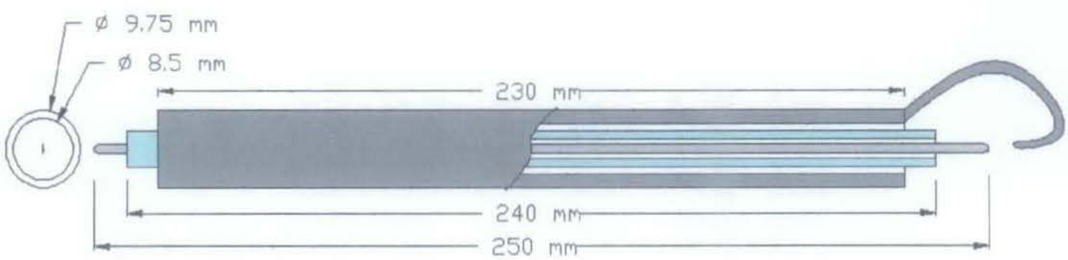


Figure 3.13: Full electrode assembly

3.8 Insulator Design Requirements

The anatomy of a spark plug is shown schematically in Figure 3.14. It is an assembly of components, one of which is the insulator. This is to be made of a ceramic, alumina, with the shape shown in an axis symmetric-hollow-stepped shape of low complexity. It weighs about 0.05 kg, has an average section thickness of 2.6 mm and a minimum section of 1.2 mm. Precision is important, since the insulator is part of an assembly; the design specifies a precision of ~ 0.2 mm and a surface finish of better than 10 mm (RMS roughness) and, of course, cost should be as low as possible. The design specification is provided in Table 3.2 (Granta, 2011).

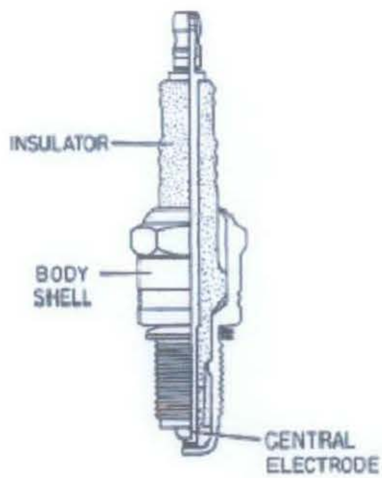


Figure 3.14: Spark plug insulator

Table 3.2: Spark plug insulator design requirements (Granta, 2011)

Material Class	Ceramics
Process Class	Primary, Discrete
Shape Class	Prismatic-axis symmetric-hollow-stepped
Mass	0.05 kg
Minimum Section	1.2 mm
Precision	0.2 mm
Surface Finish	10mm

CHAPTER 4
INITIAL RESULT AND DISCUSSION

4.1 High Current Igniter Circuit / Switching Circuit

Based on calculation in Section 3.4, the component for the circuit had been determined and the schematic for the circuit as shown in Figure 4.1. The entire component had been determined by using a simulation of electrical system to estimate the input and output power of the circuit and the time to produced it. After the schematic circuit had been drawn, it was transferred to an electrical stripboard / veroboard. It shown in Figure 4.2 where the stripboard layout can be seen mounted straight to the heat sink by using a metal oxide semiconductor field effect transistor (MOSFET) as the terminal.

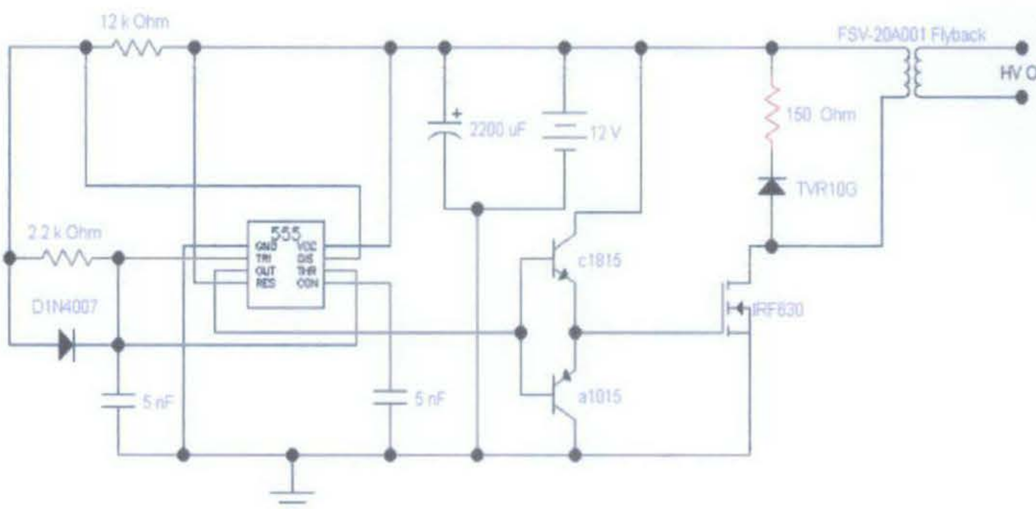


Figure 4.1: High current igniter / switching circuit

Once all the component connections were confirmed, it was fabricated and the result can be seen in Figure 4.3. Further, all the component name, type, specification and detail can be seen in Table 4.1.

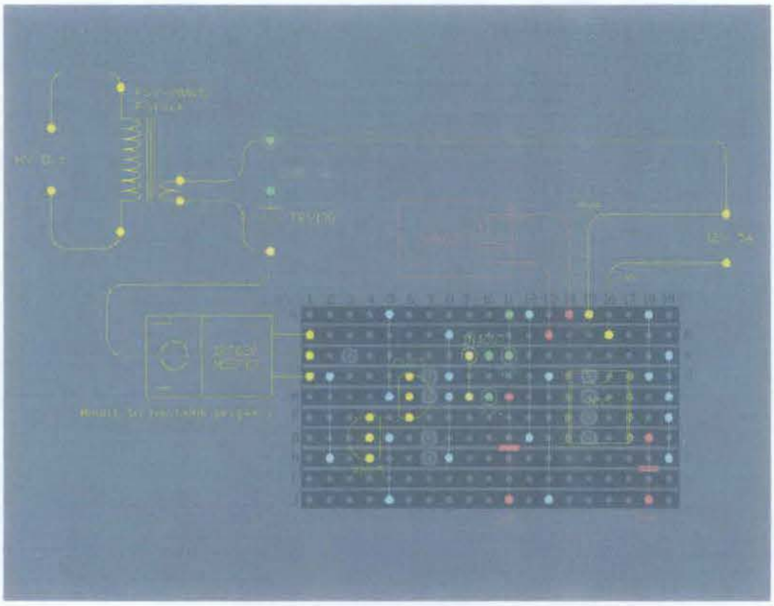


Figure 4.2: Schematic of ignition circuit component in stripboard

1: Capacitor 2200μF

2: Resistor 12 kΩ

3: Resistor 2.2 kΩ

4: Rectifier

5: MOSFET

6: Heat Sink

7: NP Capacitor

8: NP Capacitor

9: Timer

10: Transistor PNP

11: Transistor NPN

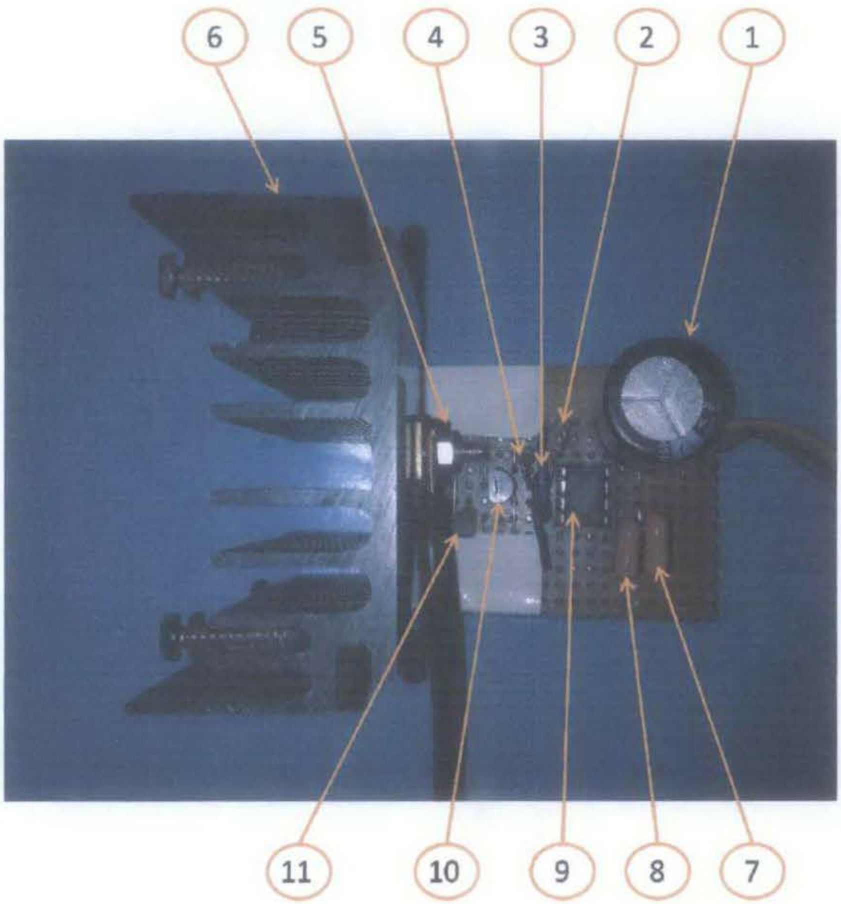


Figure 4.3: Ignition circuit components

Table 4.1: List of components

1. ELNA-RE3-35V222M-Capacitor	
Capacitor Dielectric Type: Aluminium Electrolytic; Capacitance: 2200 μF; Tolerance: ± 20 %; Voltage Rating:35 V DC	Capacitors store electric charge. They are used with resistors in timing circuits because it takes time for a capacitor to fill with charge. They are used to smooth varying DC supplies by acting as a reservoir of charge.
2. Resistor	
12 Kohms, ± 5 %	Resistors restrict the flow of electric current, for example a resistor is placed in series with a light-emitting diode (LED) to limit the current passing through the LED.
3. Resistor	
2.2 Kohms, ± 5 %	
4. Plastic Silicon Rectifier	
Voltage Range 50 To 1000 Volts, Current 1.0 Ampere	The Rectifier is an electronic device, which converts an AC waveform (Usually a Bi-directional wave form with Zero Average value) to a Pulsating DC waveform (Uni-directional waveform Nonzero Average value).
5. Powermesh MOSFET	
N - Channel 500 V - 0.75 □ - 8 A	High Current, High Speed Switching, Swith Mode Power Supplies
6. Heat Sink	
Not Available	A heat sink uses its extended surfaces to increase the surface area in contact
7. Non Polarity Capacitor 562M	
5.6 nF, Tolerance ± 20 %	A non-polarized ("non polar") capacitor is a type of capacitor that has no implicit polarity -- it can be connected either way in a circuit.
8. Non Polarity Capacitor 562M	
5.6 nF, Tolerance ± 20 %	
9. General Purpose Single Bipolar Timers	
Maximum Operating Frequency Greater Than 500 kHz	TheNE555monolithic timing circuit is a highly stable controller capable of producing accurate time delays or oscillation.
10. TO-92 Plastic-Encapsulate Transistor (NPN) C1815	
Power dissipation: PCM: 0.4, Collector current: ICM: 0.15 A, Collector-base voltage: V(BR)CBO: 60 V	Transistors amplify current, for example they can be used to amplify the small output current from a logic IC so that it can operate a lamp, relay or other high current device. The transistor also is being used to amplify voltage.
11. 2SA1015 - PNP EPITAXIAL TYPE	
VCEO = 50 V (min), IC = 150 mA (max), hFE linearity = 80 (typ.) at VCE = 6 V	Same with NPN, the main difference is that a PNP transistor uses "holes" as carriers and an NPN transistor uses electrons as carriers

4.2 Ignition Assembly

The ignition assembly full image can not be shown exactly because the picture is a little bit cloudy. Therefore, all the components pictures were captured and be connected by an arrow to show the connection towards each others. The arrow shows the picture connection neglecting the sign of plus in minus for the current movement. Figure 4.4 show the entire equipment that had been used to connect the system.

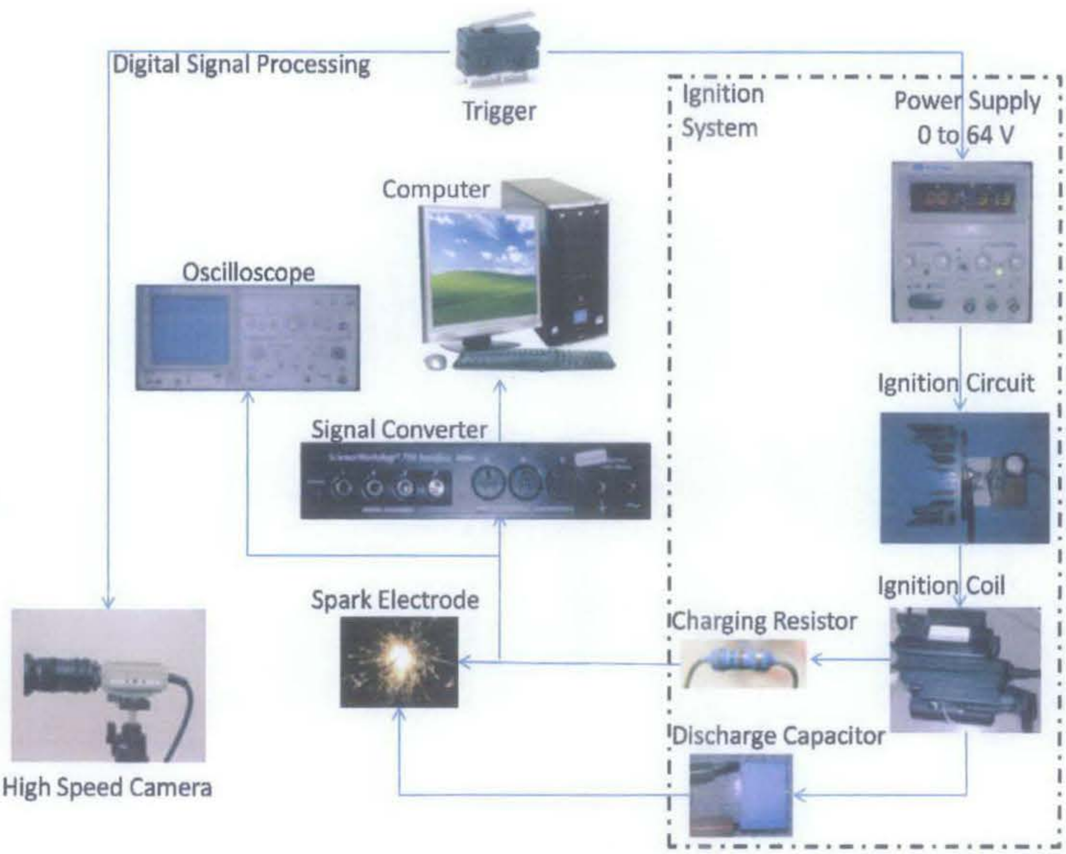


Figure 4.4: Ignition assembly

In Figure 4.4, power supply was connected to ignition circuit and ignition circuit was assembled with ignition coil to step up the voltage. The ignition coil is attached by high tension cable that withstands about 20 kV of voltage straight to the electrode. The spark electrode was attached in series by a charging resistor and in parallel by a discharge capacitor from the ignition coil. The high speed camera will attach in front of the spark electrode to capture the image of the spark to determine the spark size and its variation. An exact potential transformer needed to step down the voltage by a parallel assembly to attach the signal converter device in order to measure the exact value of voltage that will be produced. The function to do that is to measure the voltage over time (v/t) value. The voltage was then will be calculated by normal ignition coil conversion value to estimate the peak high voltage that was produced. However, because of there are no step down transformer available, the calculation of the ignition energy was based on a theoretical equation. It was based on the spark discharge theory and therefore, at this moment the used of signal converter device was neglected. The main switch was attached to a signal converter to convert the pulse that need to be sent to the ignition system and also the high speed camera. A triggered system was used to make sure both ignition system and high speed camera will work simultaneously to obtain a better results.

4.3 Spark Electrode Material Specification

The purpose of a spark electrode is to provide a place for an electric spark that is hot enough to ignite the gaseous fuel mixture inside the explosion vessel. This is done by a high voltage current arcing across a gap on the spark electrode.

A spark electrode is contains of a center electrode, an insulator and a side electrode (also called a ground electrode). The center electrode is a thick metal wire that lies lengthwise within the electrode and conducts electricity from the ignition cable hooked to one end of the plug to the electrode gap at the other end.

Based on GASEQ Software simulation for the explosion vessel, the maximum temperature and maximum pressure that create flammability in the vessel by certain fuel mixture had been determined. Therefore, the spark electrode material needs to withstand those maximum pressure and temperature that coming from the explosion vessel.

Table 4.2: Pre-ignition conditions for fuel mixture in explosion vessel (Rahman, 2010)

(a) Pre-ignition condition at 30° C and 1 bar with isentropic turbulence atmosphere

REACTANTS	UNITS	Methane/ Air flame	Hydrogen/ Air flame	Propane/ O2/ N2 Flame	Iso-octane/ O2/N2 flame
Product Temperature	K	2588	2767	2267	2641
Product Pressure	atm	8.55	7.83	1.00	9.26
Moles of Reactants	mole	0.1050	0.4200	0.0420	0.0168
Volume Products/Reactants	-	1	1	1	1
Moles Products/ Reactants	-	1.0146	0.8686	1.0500	1.0767

(b) Pre-ignition condition at 30° C and 5 bar with isentropic turbulence atmosphere

REACTANTS	UNITS	Methane/ Air flame	Hydrogen/ Air flame	Propane/ O2/ N2 Flame	Iso-octane/ O2/N2 flame
Product Temperature	K	2650	2851	2701	2712
Product Pressure	atm	43.62	40.09	46.34	47.35
Moles of Reactants	mole	0.1050	0.4200	0.0420	0.0168
Volume Products/Reactants	-	1	1	1	1
Moles Products/ Reactants	-	1.0106	0.8636	1.0535	1.0718

(c) Pre-ignition condition at 50° C and 1 bar with isentropic turbulence atmosphere

REACTANTS	UNITS	Methane/ Air flame	Hydrogen/ Air flame	Propane/ O2/ N2 Flame	Iso-octane/ O2/N2 flame
Product Temperature	K	2592	2771	2635	2645
Product Pressure	atm	8.04	7.36	8.53	8.71
Moles of Reactants	mole	0.1050	0.4200	0.0420	0.0168
Volume Products/Reactants	-	1	1	1	1
Moles Products/ Reactants	-	1.0151	0.8692	1.0587	1.0773

(d) Pre-ignition condition at 50° C and 5 bar with isentropic turbulence atmosphere

REACTANTS	UNITS	Methane/ Air flame	Hydrogen/ Air flame	Propane/ O2/ N2 Flame	Iso-octane/ O2/N2 flame
Product Temperature	K	2656	2857	2707	2718
Product Pressure	atm	41.03	37.71	43.58	44.53
Moles of Reactants	mole	0.105	0.42	0.042	0.0168
Volume Products/Reactants	-	1	1	1	1
Moles Products/ Reactants	-	1.01098	0.86409	1.05395	1.0723

Experiment will be conducted based on two fuel mixtures which are methane and iso-octane. From the simulation, the maximum pressure and temperature occurred when iso-octane fuel mixture is being put into the explosion vessel and flammability occurred. Therefore, the spark electrode material need to withstand those situations which is the maximum temperature is 2707 K or 2433^{0}C and maximum pressure is 43.58 atm or 4415 kPa.

There are lots of material can be used to develop the spark electrode. Since the spark electrode is similar with a normal spark plug, it is better to just follow the material from common spark plug to create the spark electrode. The common spark plug contains terminal electrode, ground electrode and insulator. The terminal and ground electrode are usually made from High Nickel Alloy and the insulator is made from Aluminum Oxide (alumina) Ceramic.

Nickel in elemental form or alloyed with other metals and materials has made significant contributions to our present-day society and promises to continue to supply materials for an even more demanding future. Nickel is a versatile element and will alloy with most metals. Complete solid solubility exists between nickel and copper. Wide solubility ranges between iron, chromium, and nickel make possible many alloy combinations. Stainless steels and nickel-base alloys perform well under such conditions and offer advantage in terms of reliability and lifecycle cost. They have high strength, good fabrication characteristics and can meet wide range of design requirements. Nickel is an austenite stabilizer and enhances mechanical properties and fabrication characteristics. Nickel promotes repassivation and is useful in resisting corrosion in mineral acids. Higher nickel content of about 30 % improves stress corrosion cracking (SCC) resistance. Nickel also improves high temperature oxidation resistance. Nickel alloys have good resistance to corrosion and high temperature and are also easily weldable and fabricable. Nickel maintains its FCC structure up to melting point making them ductile and tough. Nickel-base alloys, in general, have good high temperature environmental resistance and stability. They have good oxidation and carburization resistance. Heat-Resistant Applications: Nickel-base alloys are used in many applications where they are subjected to harsh environments at high temperatures.

Corrosion Resistance: Nickel-base alloys offer excellent corrosion resistance to a wide range of corrosive media. Low-Expansion Alloys: Nickel was found to have a profound effect on the thermal expansion of iron. Alloys can be designed to have a very low thermal expansion or display uniform and predictable expansion over certain temperature ranges.

The insulator is a ceramic casing that surrounds much of the center electrode; both the upper and lower portions of the center electrode remain exposed. The side electrode is a short, thick wire made of nickel alloy that is connected to the insulator and extends toward the center electrode. The tips of the side and center electrodes are adjustable so that we can study the effect of the spark gap also that creates the gap for the spark to jump across.

Aluminum oxide is an electrical insulator but has a relatively high thermal conductivity (30 $Wm^{-1}K^{-1}$) for a ceramic material. Aluminum Oxide (alumina) Ceramic has been developed and optimized for maximum wear resistance and corrosion resistance. A high density, diamond like hardness, fine grain structure and superior mechanical strength are the unique properties that make aluminum oxide ceramic the material of choice for a wide range of demanding applications. Aluminum oxide ceramic provides a cost-effective, engineered material solution in applications that require the optimum in wear resistance, corrosion resistance, and high temperature stability, and low thermal expansion, high stiffness to weight ratio, high dielectric strength and biocompatibility.

Table 4.3: Aluminum oxide (alumina) ceramic properties

Typical Properties	Units	Value
Composition	wt %	99.8 % Alumina
Color	---	White
Bulk Density	g/cm^3	3.93
Water Absorption	%	0
Gas Permeation	%	0
Grain Size	Microns	4
Hardness (Vickers)	HV	2017
Flexural strength	MPa (psi · 10^3)	382 (55)
Modulus of Elasticity	GPa (psi · 10^6)	393 (57)
Fracture Toughness	MPa · $m^{1/2}$	5
Poisson's Ratio	---	0.22
Thermal Expansion (25°C - 1000°C)	10^{-6}/°C (10^{-6}/°F)	8.2 (4.6)
Thermal Conductivity	Btu · in/ft^2 · h · °F	260
Specific Heat	cal/g · °C	.021
Maximum Temperature Use (no load)	°C (°F)	2898 (5248.4)
Dielectric Strength	ac-volts/mils	230
Dielectric Constant	---	9.7

4.4 Output Voltage

As been mentioning before, due to absence of high voltage probe gauging, the value of peak output voltage at the spark electrode has been estimated by using a Paschen's Law. Paschen found that the air breakdown voltage was described by the Equation 3.2.

In order to estimate the high peak voltage, the maximum spark gap size that the spark can occur at a certain input value has been tested. As an example for Box Blue capacitor which has 6.8 pF capacitance value, when 12 V 3.5 A input has been set from the power supply, the maximum gap that the spark can occur is 1.5 mm or $1.5x10^{-3}$ m. As a result based on Paschen's Law equation, the output voltage was 10.50 kV. The output voltage calculation can be referring in Appendix A-1. The entire calculation summary for the high output voltage is shown in Table 4.4.

Table 4.4: Calculation of output voltage by Paschen's Law

No	Capacitor Name	Input Voltage, (V)	Input Current, (A)	Capacitance, (pF)	Maximum Gap, mm	Output Voltage, kV
1	Box Blue	12	3.5	6.80	1.5	10.50
2	Box Blue	12	4.0	6.80	2.0	13.39
3	Box Blue	12	4.5	6.80	2.5	16.19
4	Flat Blue	12	3.5	4.72	2.0	13.39
5	Flat Blue	12	4.0	4.72	2.5	16.19
6	Flat Blue	12	4.5	4.72	3.0	18.92
7	Big Blue	12	3.5	1.00	2.0	13.39
8	Big Blue	12	4.0	1.00	3.0	18.92
9	Big Blue	12	4.5	1.00	4.0	24.23
10	Big Brown	12	3.5	1.00	2.0	13.39
11	Big Brown	12	4.0	1.00	2.5	16.19
12	Big Brown	12	4.5	1.00	3.5	21.60

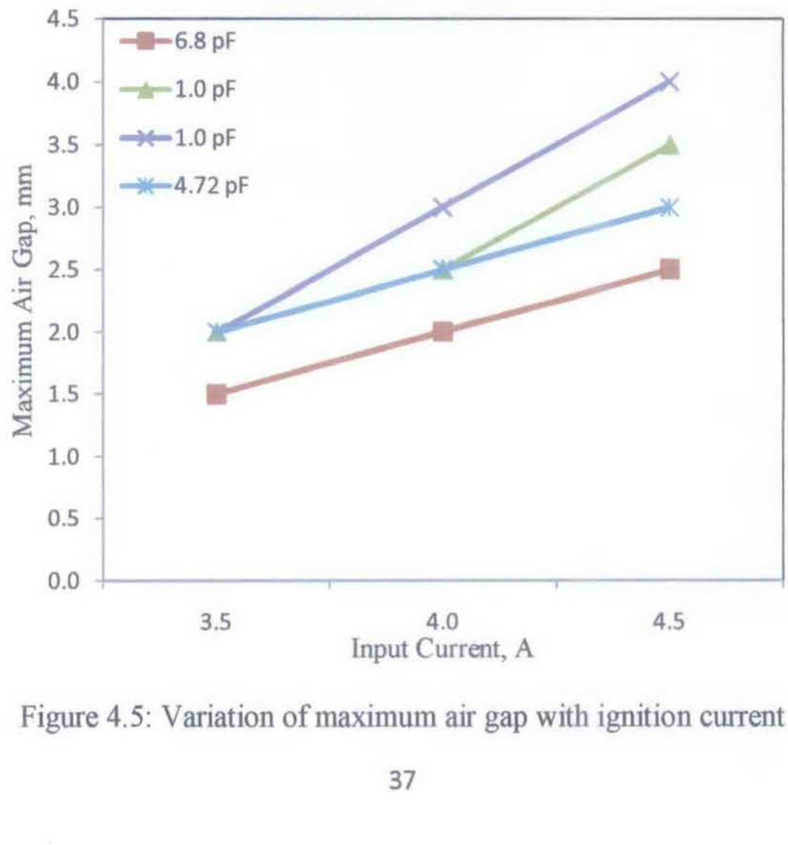


Figure 4.5: Variation of maximum air gap with ignition current

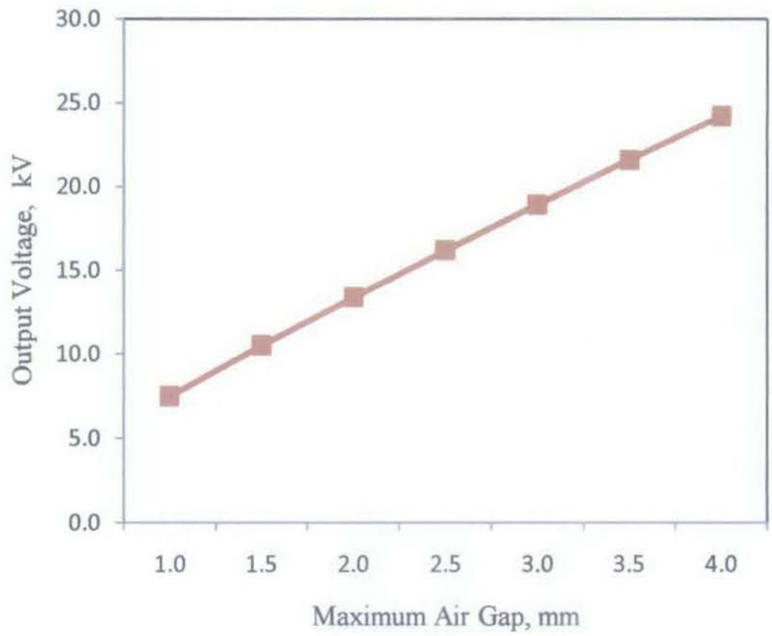


Figure 4.6: Variation of output voltage with maximum air gap

As been stated in the Table 4.4, the output voltage is affected much by ranging the input current. For those four values of capacitor, each of them gave higher energy when the input current was increased. This is because of the step up transformer that being used. The principal of the flyback transformer is stated that the input current will give affect towards the output voltage that will be produced. The actual spark is generated when the breaker contacts open. For an ideal inductor, the current and voltage relate by:

$$V = L\ dI \qquad (4.1)$$

where V is voltage, L is inductance (in henrys) and dI is the rate of change of the current. Thus, seeing that L is constant for the inductor, the abrupt change in current will cause a very large voltage to be produced. This produces in a very short, very high voltage spike. The change in current is on the primary side, but because the primary and secondary coils have a large mutual inductance (this is where the transformer part comes in), it gave a spike on the order of 100 or more volts on the primary, and more than 10000 volts on the secondary.

The breakdown voltage of parallel plates in a gas is a function of pressure and gap distance (Paschen, 1889). The mean free path of a molecule in a gas is the average distance between its collisions with other molecules. This is inversely proportional to the pressure of the gas. In air, the mean free path of molecules is about 96 nm. Since electrons are much smaller, their average distance between colliding with molecules is about 5.64 times longer or about 0.5 μm. This is a substantial fraction of 7.5 μm spacing between the electrodes for minimum arc voltage (Paschen, 1889). If the electron is in an electric field of 43 MV/m, it will be accelerated and acquire 21.5 electron volts of energy in 0.5μmof travel in the direction of the field. The first ionization energy needed to dislodge an electron from nitrogen is about 15 eV. The accelerated electron will acquire more than enough energy to ionize a nitrogen atom. This liberated electron will in turn to be accelerated which will lead to another collision. A chain reaction then leads to avalanche breakdown and arc takes place from cascade of released electrons.

4.5 Spark Energy Estimation

Ignition energy is the amount of energy that an electric spark discharge have to deliver the ignition of a given gas mixture at given conditions or at atmosphere. In the present study, the ignition energy reported is actually the energy stored in the capacitor used to create the electrical discharge. The stored energy was varied by using different combinations of capacitors and different charging voltages from 1 kV to 24 kV by the Paschen's Law calculation. Voltage was predicted as the capacitor was charged, and the spark was triggered when the desired charging voltage was reached and stabilized. The energy stored in the capacitor that had been computed from the standard relationship in Equation 3.4.

For a Box Blue 6.8 pF capacitor, with an input voltage 12 V and 3.5 A, the estimation of the peak voltage from Table 4.3 is 10.50 kV therefore, the ignition energy that been produced was 0.3749 mJ. The ignition energy calculation can be referring in Appendix A-2. The entire calculations summary for the ignition energy is shown in Table 4.5.

Table 4.5: Calculation of ignition energy

No	Capacitor Name	Capacitance Value, pF	Input Voltage, V	Input Current, A	Output Voltage, kV	Ignition Energy, mJ
1	Box Blue	6.80	12	3.5	10.50	0.3749
2	Box Blue	6.80	12	4.0	13.39	0.6096
3	Box Blue	6.80	12	4.5	16.19	0.8912
4	Flat Blue	4.72	12	3.5	13.39	0.4231
5	Flat Blue	4.72	12	4.0	16.19	0.6186
6	Flat Blue	4.72	12	4.5	18.92	0.8450
7	Big Blue	1.00	12	3.5	13.39	0.0897
8	Big Blue	1.00	12	4.0	18.92	0.1790
9	Big Blue	1.00	12	4.5	24.23	0.2937
10	Big Brown	1.00	12	3.5	13.39	0.0897
11	Big Brown	1.00	12	4.0	16.19	0.1311
12	Big Brown	1.00	12	4.5	21.60	0.2333

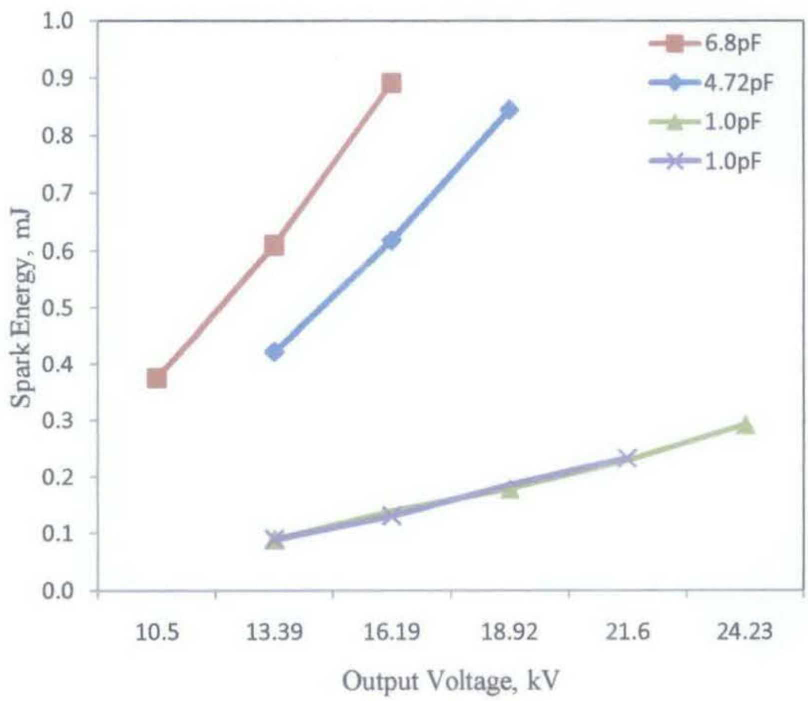


Figure 4.7: Variation of spark energy with output voltage

The ignition energy is actually the energy stored in the capacitor used to create the electrical discharge. The stored energy was varied by using different value of capacitors. High voltage was used to charge the capacitor, and the spark was triggered when the desired charging voltage was reached and stabilized. From the graph that been obtained, the spark energy was depending much on capacitor value. For same value of output voltage as an example 13.39 kV, 6.8 pF capacitor gave 0.6096 mJ, 4.72 pF capacitor gave 0.4231 mJ and 1.0 pF capacitor gave 0.0897 mJ. This shown that in order to obtain a higher amount of spark energy, higher capacitance value need to be added into consideration. For this experiment, 6.8 pF capacitor that can produced 0.8912 mJ which is highest amount of energy is enough for being tested.

4.6 Spark Ignition Kernel Size

The size of the spark kernel had been captured by Phantom V9 high speed camera. A system was assembling with one unit of trigger system which is then converted the information to start capturing the image and also release the spark at the spark electrode simultaneously. The resolution of the camera had been set to be 96 x 48 and the capturing image was set to catch 80000 fps which can be explain in a second, 80000 image had been captured. In other way, each image had been captured in every 12.5 μs. The grid had been installed at the back of the spark electrode to guide the spark size measurement. Once the spark had been captured, by using the phantom software, the size of the spark had been measured based on the grid. For a comparison of size, all type of capacitor had been test start from 12 V 3.5 A input until 12 V 4.5 A. For each different of current input, three spark gap lengths were manipulated to see the effect of the gap to the spark size also. The gap had been set to be 0.5 mm for the start, followed by 1 mm and 2 mm. The reason to catch the image at the maximum of 2 mm because of 2 mm is the smallest gap that minimum energy can deliver the spark. Therefore, the comparison can be made start from the smallest amount energy until the biggest amount of energy by all those three gap length value. Table 4.6 to Table 4.8 shows the ignition energy and the spark kernel size image together with the spark vertical size.

Table 4.6: Spark size and image for I = 3.5A

Test No	Capacitor Name	Input Current, (A)	Ignition Energy, (mJ)	Gap Length, (mm)	Spark Size, (mm)	Spark Image
1	Box Blue	3.5	0.3749	0.5	2.948	
2	Box Blue	3.5	0.3749	1.0	4.960	
3	Box Blue	3.5	0.3749	2.0	6.876	
4	Flat Blue	3.5	0.4231	0.5	3.025	
5	Flat Blue	3.5	0.4231	1.0	5.018	
6	Flat Blue	3.5	0.4231	2.0	6.983	
7	Big Blue	3.5	0.0897	0.5	1.503	
8	Big Blue	3.5	0.0897	1.0	1.858	
9	Big Blue	3.5	0.0897	2.0	3.244	
10	Big Brown	3.5	0.0897	0.5	1.376	
11	Big Brown	3.5	0.0897	1.0	2.492	
12	Big Brown	3.5	0.0897	2.0	3.011	

Table 4.7: Spark size and image for I = 4.0A

Test No	Capacitor Name	Input Current, (A)	Ignition Energy, (mJ)	Gap Length, (mm)	Spark Size, (mm)	Spark Image
1	Box Blue	4.0	0.6096	0.5	3.655	
2	Box Blue	4.0	0.6096	1.0	5.306	
3	Box Blue	4.0	0.6096	2.0	7.044	
4	Flat Blue	4.0	0.6186	0.5	3.721	
5	Flat Blue	4.0	0.6186	1.0	5.531	
6	Flat Blue	4.0	0.6186	2.0	7.113	
7	Big Blue	4.0	0.1790	0.5	1.685	
8	Big Blue	4.0	0.1790	1.0	1.834	
9	Big Blue	4.0	0.1790	2.0	3.303	
10	Big Brown	4.0	0.1311	0.5	1.758	
11	Big Brown	4.0	0.1311	1.0	2.532	
12	Big Brown	4.0	0.1311	2.0	3.488	

Table 4.8: Spark size and image for I = 4.5A

Test No	Capacitor Name	Input Current, (A)	Ignition Energy, (mJ)	Gap Length, (mm)	Spark Size, (mm)	Spark Image
1	Box Blue	4.5	0.8912	0.5	4.217	
2	Box Blue	4.5	0.8912	1.0	6.087	
3	Box Blue	4.5	0.8912	2.0	7.513	
4	Flat Blue	4.5	0.8450	0.5	4.104	
5	Flat Blue	4.5	0.8450	1.0	5.964	
6	Flat Blue	4.5	0.8450	2.0	7.468	
7	Big Blue	4.5	0.2937	0.5	1.799	
8	Big Blue	4.5	0.2937	1.0	1.962	
9	Big Blue	4.5	0.2937	2.0	2.437	
10	Big Brown	4.5	0.2333	0.5	2.035	
11	Big Brown	4.5	0.2333	1.0	2.696	
12	Big Brown	4.5	0.2333	2.0	3.617	

The shape of a spark kernel obtained without special measures is in general neither regular nor fixed in time. The projected area of the kernel is measured in such cases to compute an equivalent radius which is often the radius of a sphere with the same projected area. The equivalent radius is a representative dimension of the kernel, but may give an inadequate estimate of the volume or surface area because of the spherical symmetry assumed in the conversion. The effect of varying spark energy on spark kernel can be seen in Figure 4.8. The coil primary current is varied to obtain spark energies of approximately from 0.0897 mJ to 0.8912 mJ. These ignition energies range from near the minimum level to a certain level which the ignition circuit can support the charging. The size of the spark kernel can be seen as small as 1.503 mm to the biggest size which is 7.513 mm. The interesting part comes when the largest size of spark kernel can easily be obtained by using higher value of discharge capacitor. As an example from the Table 4.5, with same amount of output voltage which is 13.39 kV, quite a large different value of ignition energy can be seen based on value of discharge capacitor that being used. As a result of that, different large size of spark kernel had been captured. As what can be observed, the spark size first surely was affected by input primary current which will generate a different amount of ignition energy.

The second observation can be seen when ranging the spark gap between the electrodes. As what can be seen, the spark goes a little bit bigger when the spark gap was increased. There are largest gap that stop the spark to occur because of the spark can not break that longest gap. However, below that limit of gap as an example for Box Blue capacitor, when 12 V 4.5 A supply had been put, the maximum gap the spark can occur was 2.5 mm. Therefore, right below the 2.5 mm was the largest size the spark will occur. As we decrease the gap, the spark size will also decrease. This can be explained because of more collisions will take place in the electron path between the electrodes. When the pressure gap product, pd is high, an electrons will collide with many different gas molecule as it travels from cathode to anode. Each of the collisions randomizes the electrons directions, so the electrode is not always being accelerated by the electric field but sometimes also it travels back towards the cathode and is decelerated by the field. This will help produced a larger spark size when a larger gap was put in action. The summary of the spark size had been tabulated in Figure 4.8.

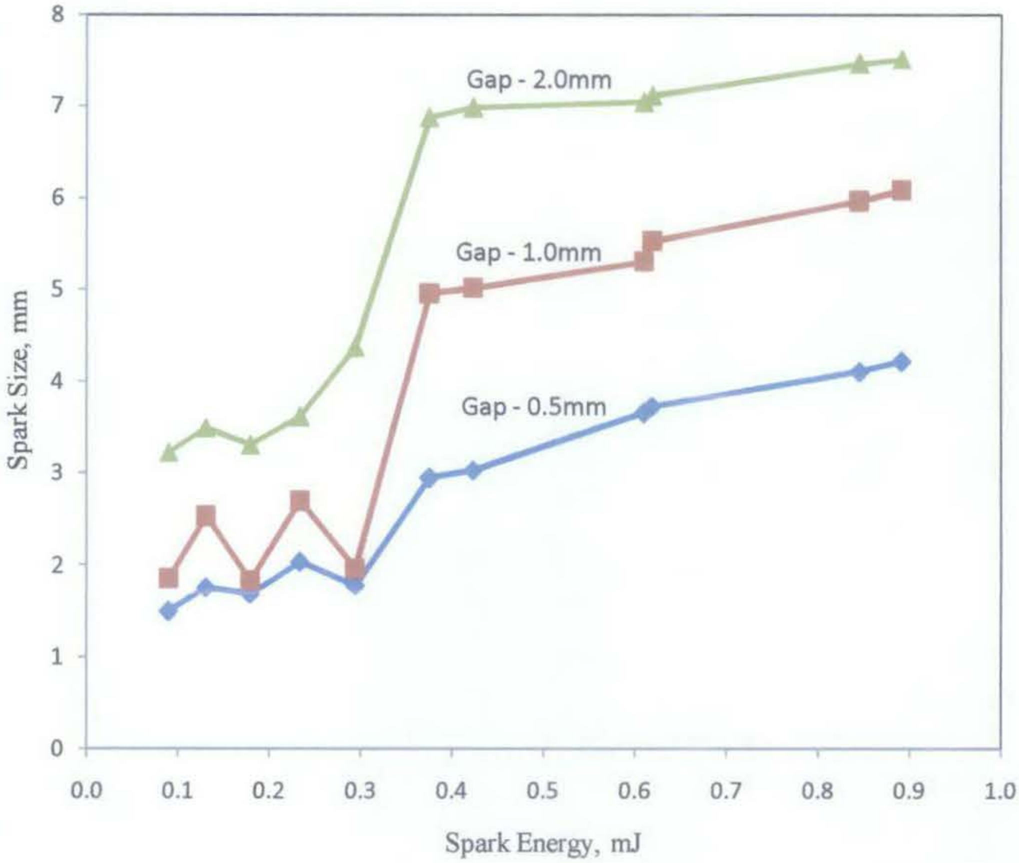


Figure 4.8: Variation of spark size with spark energy

From Figure 4.6, clearly we can see with a same amount of energy, different spark gap give different spark kernel size. The higher the gap, the bigger the size of the spark kernel will be obtained until the limit of the spark gap is reach where no spark can occur due to very large gap that does not permit the spark to occur due to less energy. The are also several factor that affect the spark size and some of the most important factor that was observed during the experiments was the gas temperature and pressure. All the experiment was done in open area, therefore it was assumed that the gas will follow atmospehere temperature and pressure. However, some of the experiment had been done in laboratory and the temperature in the laboratory was always maintained to be 21° C by a temperature sensor. Initially, some experiments had been done at the outside of laboratory and the size of spark that had been observed was a little bit bigger. It is because the outside temperature were the standard atmospheric temperature which is 37° C. Therefore, in order to counter that all experiments had been done at the outside of laboratory to obtain larger spark size at the atmospheric temperature.

In Figure 4.8, the affect of capacitance value and the spark gap can be seen much clearly. Higher capacitance value sure will give higher value of ignition energy and higher spark gap will increase the spark size until the limit. As what can be seen, the highest spark size that was obtained from the experiments was almost 8 mm in size which was being conduct by 4.5 A of input current with largest gap for this experiment which is 2.0 mm of gap. From both graph, there are some value that reverse the conclusion that was obtained. Clear view can be seen from Figure 4.9 when referring to 1.0 mm of gap. When 0.1306 mJ of energy was supplied, the spark size was larger than 0.1790 mJ of energy. This might be the affect of electrode temperature and the transformer misfunction due to lots of use in a short period of time. From those experiments, it can be clearly stated that spark size kernel was depending on spark energy that being supply and spark gap that being used.

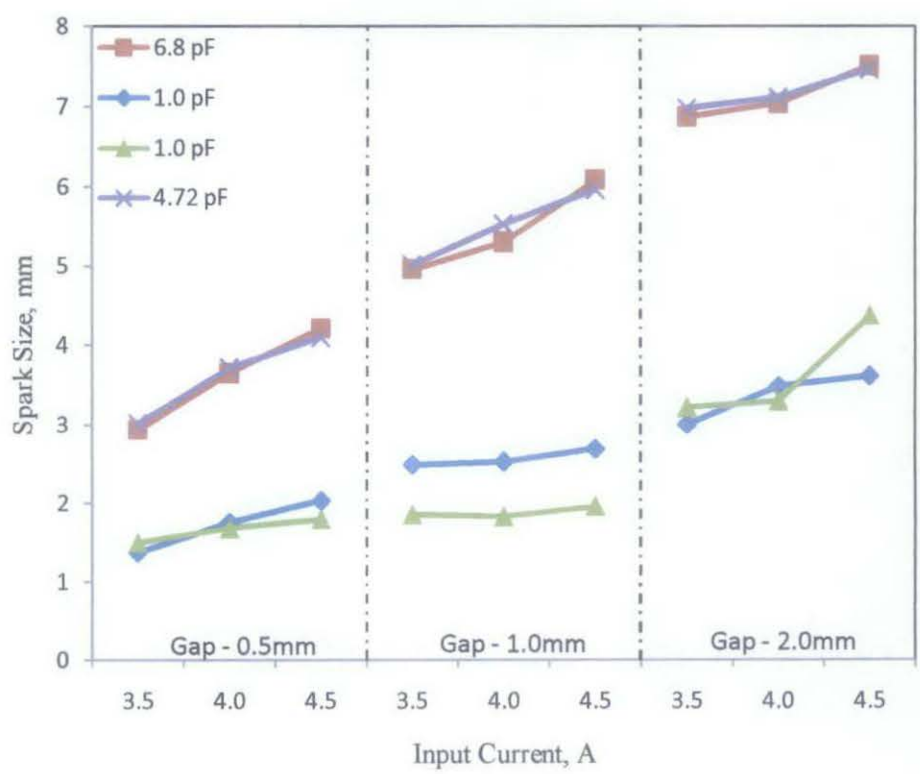


Figure 4.9: Variation of spark size with different input current

4.7 Variation of Spark Development

A high speed photographic record provides a valuable history of the shape and size of a developing flame kernel. A variation of the temporal distribution of the spark energy influences the minimum ignition energy as well as the rate of kernel growth (Kono, 1976). The experimental part of the present study provides some high speed movies of developing spark kernels. A shutter speed of 12.5 µs and framing rate of 80,000 fps is used for this investigation with a spark gap of 2.0 mm. Numbers below the pictures represent the elapsed time in microseconds after spark initiation. The pictures are from a continuous recording of a single spark event.

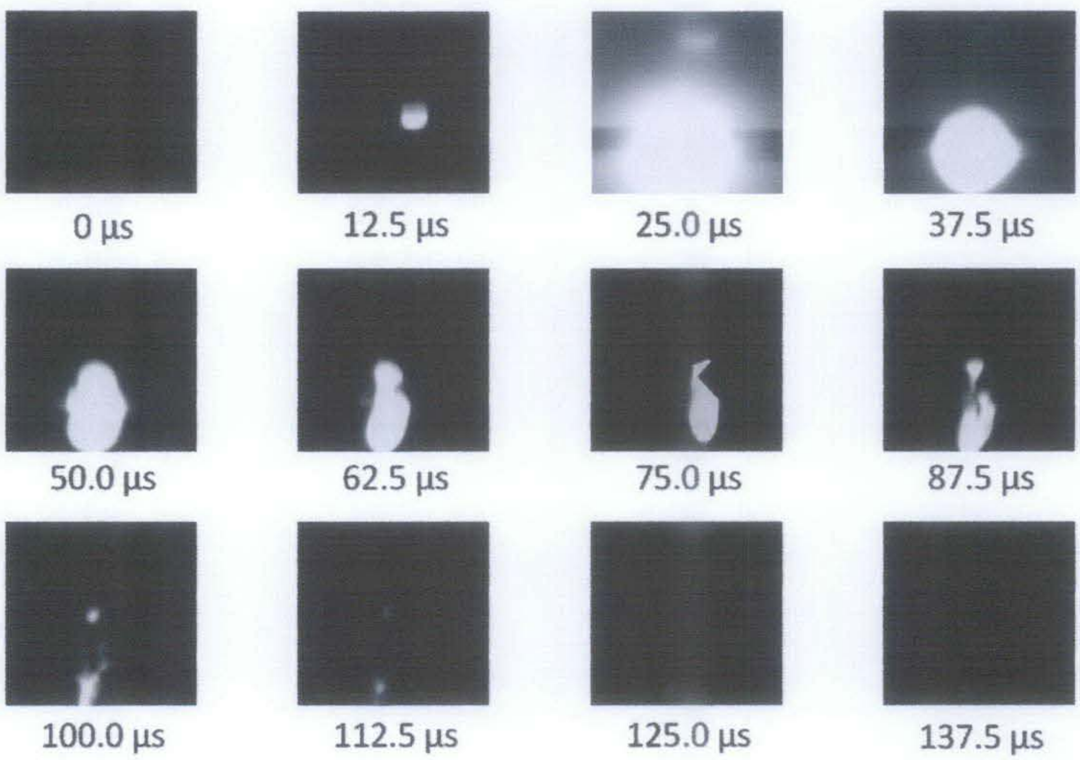


Figure 4.10: Natural light imaging of electric spark development in standard atmosphere condition

The first frame shows the high temperature kernel and the ellipsoidal trace of a weak shock wave that are generated by the breakdown event. The boundary of the kernel is wavy during the initial 12.5 µs – 25.0 µs, but smoothes out in time. The wavy boundary of the kernel is observed in all of the cases studied and appears to be a result of the turbulence created by the blast during the breakdown of the gap. The experimentally measured spark kernel radii appear to show that the kernel development is due to a diffusive process within a few microseconds after the breakdown event. This comes from the observation that the temporal variation of the kernel radius resembles a geometric parabola as been captured in sequence of Figure 4.8. The initial growth after spark initiation appears to be faster than by diffusion alone. As a result, the kernel appears to start from a finite size at time zero. However, the inception of spark development can not be captured in sequence even though the maximum frame per second from the camera had been used. In the second picture which is 25.0 μs, the spark already reaches the maximum size that it can produce. The reducing spark from the highest size to the last small light before it disappeared can be viewed in a good sequence. Start from 37.5 μs until 87.5 μs, the spark was reduced in sequence and manage to be captured by the high speed camera. This might be because the initiate spark was much faster that the decreasing. When reach 100 μs of time, the picture shows the left smoke that been released from the spark ignition. The measured kernel radii show a small difference in size that favors the lower power case immediately after spark initiation. This subtle difference persists throughout the time period of measurement 87.5 μs. Table 4.9 shows the spark size development with respect to time.

Table 4.9: Variation of spark size at a certain period of time duration

Time, μs	Spark Size, mm
0	0
12.5	0.505
25.0	5.377
37.5	4.892
50.0	3.781
62.5	3.229
75.0	3.068
87.5	2.891
100.0	1.782
112.5	0.403
125.0	0.113
137.5	0

A comparison of breakdown voltages reveals that the spark energy that been produced from the discharge capacitor was being supplied in a certain period of time which is believed to be responsible for the initial size difference until the growth. , However, the difference in radius is statistically insignificant, especially after 12.5 μs because the initiation of the spark was very fast. One concludes that a factor of about the amount of the spark energy results in the development of spark kernel. Therefore, in order to obtain the initiation sequences, higher spark energy need to use. The summary of the sequence of spark development size had been plotted in Figure 4.11. The initially rapid growth of the kernel during the spark discharge can be adequately predicted with a mass entrainment term that is a function of the electrical power input. Kernel radii of equivalent sparks in atmosphere exhibit a difference as early as 12.5 μs after breakdown. This suggests that kernel growth by chemical energy release occurs very early in the process.

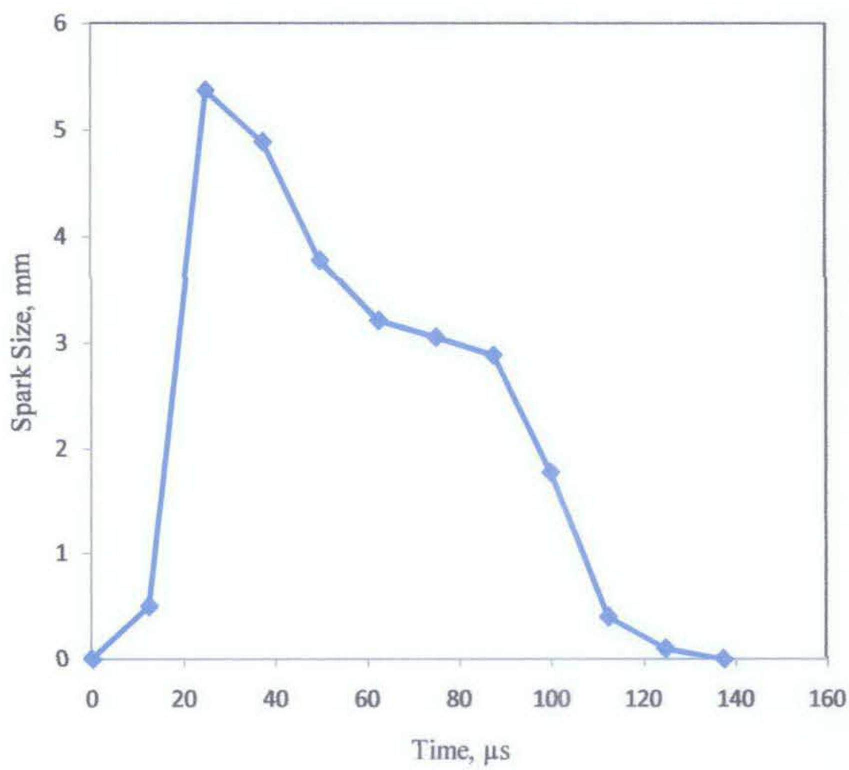


Figure 4.11: Variation of spark size with time from initial of ignition

4.8 Fabrication of Spark Electrode

The spark electrode had been fabricate based on design that been put in methodology. The material had been stated to be high nickel alloy for the ground electrode and center electrode and ceramic for the insulator. However, due to difficulty in getting a high nickel alloy and difficulty in cutting the metal, both center electrode and ground electrode materials had been change to stainless steel. The explosion the will be created just take a very short time which is around a miliseconds. Therefore, eventhough the temperature was explosion was very high for a stainless steel but it still can be used because of the duration of explosion was very short. The complete assembly of all the electrode components can be seen in Figure 4.12.

Figure 4.12: Complete fabricated spark electrode

Due to a time constraint, it was difficult to determine the very suitable spark electrode for the vessel. Therefore, design of the spark electrode was created just based on the size of the explosion vessel. The calculation of the spark electrode size can be seen in the methodology parts. The spark electrode was created just based on the size of explosion vessel but the most important thing was wether it can be function in good condition and is the insulator can perform its task perfectly. The spark electrode had been test by the ignition system and it can work perfectly.

Next is to determine the functionality of the insulator. At first, the insulator had been fabricated based on common spark plug insulator thickness. As been stated in Table 3.2, the minimum thickness for a common spark plug is 1.2 mm. Therefore, 2 mm of ceramic had been manufactured to function as an insulator between those ground electrod and center electrode. In order to determine whether the insulator can perform its task, a Digital Multi Function Tester Model 6011 gauge had been used to determine the leakage at the insulator. The insulatin between conductors have a potential difference between them which is the cathode and the anode for the spark electrode that behaves as the dielectric of a capacitor. When a direct high voltage is applied to the electrode, a charging current will flow to the system which will die away to zero. Since the insulation resistance is not finite, a small leakage current flows through the insulation between both electrodes. Since Ohm's Law applies, the leakage current can be calculated by Equation 4.2.

$$\text{Leakage current } (\mu m) = \frac{\text{Applied voltage (V)}}{\text{Insulation resistance } (M\Omega)} \tag{4.2}$$

Based on Digital Multi Function Tester gauge, three test had been done towards the spark electrode to determine the leakage current. The maximum applied voltage that the gauge can be set was 1000V. The result of the test can be viewed in Figure 4.13.

Figure 4.13: Insulation results from digital multi function tester

From those three test, the mean average of the insulation resistance had been determined. The amount of leakage current had been calculated based on Equation 3.5. The result is shown in Figure 4.11 was used on calculation in Appendix A-3. As a result, the insulation resistance for the spark electrode was 19.01 MΩ. Based on the insulation test, the amount of leakge current was calculated to be very small as 52.59 μA. The calculation can be viewed in Appendix A-4. This amount of leakage current is low enough compared to the 3.5 A minimum current that was supplied. The percentage of leakage current was calculated to be just 1.50 %. This amount of leakage current can not be avoided due to the condition of surface of the insulation between the electrode conductor. If the surface of the insulator are clean and dry, the amount of leakage current can be reduced. The leakage current depends upon the surface insulator that are clean and dry. As a conclusion from this test, the amount of leakage current had not been take into consideration due to the very low of value.

The thermal conductivity of a metal is greater than that of a gas by at least two orders of magnitude. Since a spark kernel is in contact with the electrodes throughout its developing stage, a measurable amount of energy can be lost from the kernel to the electrodes through conduction, convection, and chemical recombination at the surface. This is especially true with massive electrodes. Efforts are usually made in experimental studies of spark ignition to reduce these effects by installing small electrodes and using a gap that is wider. There currently are no spark ignition models that include the effect of heat transfer to the electrodes. It is an important factor to be considered because automotive spark plugs typically have electrodes whose dimensions are of the same order as the gap dimension. In an investigation of electrode heat transfer, (Roth, 1951) compute the percentage of spark energy that remains in the gas after a short capacitive spark from the measured pressure or volume increase in a vessel. The maximum thermal energy in the gas is observed to occur immediately after the spark and increases with increasing gap width and decreasing electrode diameter as one would expect. Therefore, in this experiment, the center electrode had been set to be 2 mm to give the smallest electrode size that will help to reduce the heat transfer towards the electrode.

4.9 Ignition by Spark

The ignition system supposely need to be test in the explosion vessel. However, the fabricatio of the explosion vessel is still in progress by the manufacturer. Therefore, the system can not be test wether its work or not. Therefore, in order to determine wether the system is function to create the ignition or not, the system was test towards a bunsen burner. The bunsen burner contains a butane gas. The experiment had been done in open area which is subjected to atmosphere condition. Butane is a gas with the formula C_4H_{10} that is an alkane with four carbon atom. Butane are highly flammable, colorless and easily liquefied gas. When oxygen is plentiful, butane burns to form carbon dioxide and water vapor, but when oxygen is limited, a carbon monoxide may also be formed. In this experiment, the ignition had been done in open area to provide enough oxygen to the gas to ignite by the spark. The maximum adiabatic flame temeperature of the butane with air at atmospheric condition is 2243 K or 1970°C. All the capacitor with ranging amount of input current that affect the ignition energy had been test towards the igntion of the butane gas. Further, the spark gap also had been manipulated to see the affect of spark size towards the ignition of butane. The summary of butane ignition by the spark can be viewed in Table 4.10 to Table 4.13.

Table 4.10: Igntion of butane gas by box blue capacitor

Test No	Capacitance Value, (pF)	Input Current, (A)	Gap Length, (mm)	Ignition Energy, (mJ)	Spark Size, (mm)	Ignition / No-Ignition (1/0)
1	6.8	3.5	0.5	0.3749	2.948	1
2	6.8	4.0	0.5	0.6096	3.655	1
3	6.8	4.5	0.5	0.8912	4.217	1
4	6.8	3.5	1.0	0.3749	4.960	1
5	6.8	4.0	1.0	0.6096	5.306	1
6	6.8	4.5	1.0	0.8912	6.087	1
7	6.8	3.5	2.0	0.3749	6.876	1
8	6.8	4.0	2.0	0.6096	7.044	1
9	6.8	4.5	2.0	0.8912	7.513	1

Table 4.11: Igntion of butane gas by flat blue capacitor

Test No	Capacitance Value, (pF)	Input Current, (A)	Gap Length, (mm)	Ignition Energy, (mJ)	Spark Size, (mm)	Ignition / No-Ignition (1/0)
10	4.72	3.5	0.5	0.4231	3.025	1
11	4.72	4.0	0.5	0.6186	3.721	1
12	4.72	4.5	0.5	0.8450	4.104	1
13	4.72	3.5	1.0	0.4231	5.018	1
14	4.72	4.0	1.0	0.6186	5.531	1
15	4.72	4.5	1.0	0.8450	5.964	1
16	4.72	3.5	2.0	0.4231	6.983	1
17	4.72	4.0	2.0	0.6186	7.113	1
18	4.72	4.5	2.0	0.8450	7.468	1

Table 4.12: Igntion of butane gas by big blue capacitor

Test No	Capacitance Value, pF	Input Current, A	Gap Length, mm	Ignition Energy, mJ	Spark Size, mm	Ignition / No-Ignition (1/0)
20	1.0	4.0	0.5	0.1790	1.685	0
21	1.0	4.5	0.5	0.2937	1.799	0
22	1.0	3.5	1.0	0.0897	1.858	0
23	1.0	4.0	1.0	0.1790	1.834	0
24	1.0	4.5	1.0	0.2937	1.962	1
25	1.0	3.5	2.0	0.0897	3.244	1
26	1.0	4.0	2.0	0.1790	3.303	1
27	1.0	4.5	2.0	0.2937	4.377	1
20	1.0	4.0	0.5	0.1790	1.685	0

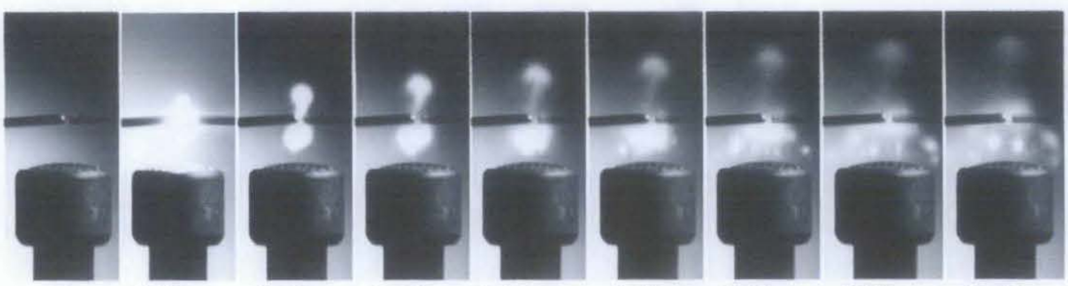
Table 4.13: Igntion of butane gas by big brown capacitor

Test No	Capacitance Value, pF	Input Current, A	Gap Length, mm	Ignition Energy, mJ	Spark Size, mm	Ignition / No-Ignition (1/0)
28	1.0	3.5	0.5	0.0897	1.376	0
29	1.0	4.0	0.5	0.1311	1.758	0
30	1.0	4.5	0.5	0.2333	2.035	0
31	1.0	3.5	1.0	0.0897	2.492	0
32	1.0	4.0	1.0	0.1311	2.532	1
33	1.0	4.5	1.0	0.2333	2.696	1
34	1.0	3.5	2.0	0.0897	3.011	1
35	1.0	4.0	2.0	0.1311	3.488	1
36	1.0	4.5	2.0	0.2333	3.617	1

From the igntion of butane gas Table 4.10, the things that affected the ignition was the ignition energy and the spark gap. For box blue capacitor, all the igntion energy and spark gap can igntite the gas. Same things goes to a flat blue capacitor. This is due to high ignition energy that had been produced. However, for a big blue and big brown capacitor which can produced maximum of 0.2937 mJ energy, 0.5 mm gap can not ignite the gas. This can be explained due to the effect of spark size that had been produced. From the Table 4.7, the minimum required spark size that can ignite the gas was 1.962 mm. However, for test number 31, the spark size was 2.492 mm still can not ignite the butane gas. This is due to the small ignition energy that the system had.

Therefore, the ignition system can be explained to affected by a three factor which is the spark energy, spark gap and also the spark size. In Appendix B-1, the sequence of ignition system for the butane gas had been captured by the high speed camera. The shutter had been set to capture 13000 picture in a seconds which can be explained to be 13000 fps. This camera setting will captured a picture in every 77 μs. From the sequence of igntion, at duration 77 μs the small spark kernel that has high temperature can be seen before it start to explode the gas the time duration 154 μs. The gas the started to get burned at 231 μs until 1000 μs where the gas start to ignite the whole gas that being press out from the bunsen burner. The size of the ignition gas can be seen increase from 1000 μs until 3000 μs. The increase in size of the butane gas can not be seen clearly because the igntion had been push by a high pressure butane gas that come out from the bunsen burner. At time duration of 3000 μs the ignition system was fully complete where the flame can be seen produced from the gas that being released by the bunsen burner. From the sequence og ignition, estimately the total time to ignite the flame was around 3000 μs which equivalent to 3 ms. At time 3076 μs, the gas that come out from the bunsen burner can be seen started to get completely burned.

Basically, the function of doing this test was not to study the igntion of the bunsen burner. However, its just a test to determine wether the ignition system can work perfectly or not. Therefore, from those test it can be clearly said that the system can function properly and it can be used in the explosion vessel to igntite the explosion later. A much clearer view of the ignition of butane gas can be seen in Figure 4.14 where the frame per second of capturing image had been reduced to 1200 fps.



0 0.83 ms 1.67 ms 2.50 ms 3.33 ms 4.17 ms 5.00 ms 5.83 ms 6.67 ms

Figure 4.14: Sequence images of ignition for a bunsen burner from initial of ignition with spark energy of 0.8912 mJ and spark gap 2.0 mm

This can be explained as in every 0.83 ms of time duraition, one picture was captured. The ignition can be seen start at 0.83 ms where the spark start to break the air gap. The size of the ignition gas increase until 3.33 ms of time duration before the gas that come out from the bunsen burner started to get burned. Same things goes at the previous sequence of picture where at around 3000 μs, the biggest size of the gas ignition size before the whole gas started to get burned. It can be conclude that to ignite the butane gas, 3 ms of time duration was needed before it can reach a complete combustion. Finally, as been stated before, the system was tested and can be used in perfect condition to perform its task in the explosion vessel.

CHAPTER 5
CONCLUSIONS

5.1 Overall Conclusions

From the research that had been done so far show that a reliable spark ignition system with a proper design constraint for the spark electrode had been develop. Therefore, the objective of this project had been meeting. There are lots of factor that will affect the ignition system whether it affect the spark energy or the spark electrode reliability. Some of the affect such as spark gap, spark electrode size, voltage produce, equation for energy calculation and electrode material had been took in action. The other affect such as design constraint, temperature and pressure affect, gaseous fuel mixture affect had been put aside because of the explosion vessel is still in a fabrication progress. The spark had been captured in a good technique by using the high speed camera, Phantom V9.1. In other side, the electrode had been manufacture by the help of a manufacturing company. The insulator had been made by a ceramic material which is custom made by very high firing of temperature. It is difficult to determine the exact value manufacture or made the insulator. Therefore, the spark electrode was first being fabricated based on normal spark plug design requirements and later, the electrode was tested and the result shows that the electrode can deliver the spark perfectly. The next step towards the spark electrode was to test the insulation whether it was good to insulate between the ground electrode and the central electrode. By using Digital Multi Function Tester, the amount of leakage current had been found to be very low that just a micro ampere and therefore it can be neglected.

Ignition energy is a vital element of the performance of an ignition system, which is based on the integral calculation of ignition voltage and ignition current, and reflects the combustion state of the engine system. Energy provided by the ignition system must be ensured adequate to ignite combustible mixture under different conditions. The ignition energy had been determined based on discharge capacitor method. This is where the capacitor was charge by a high voltage input and being discharge through the spark gap when the circuit was being opened. The high output voltage had been determined by a Paschen's Law and the value was used to calculate the ignition energy.

In the experiment, the size of spark discharge had been taking as results. The spark size was found depend upon several factors which are the spark energy, discharge capacitor value and also the spark gap. Higher spark energy and higher discharge capacitor value for sure was gave larger spark size. Instead of that, the spark gap also affected the spark size which is increasing the spark gap will increase the spark size until a certain maximum gap that stop the spark to break the long air gap. The size of spark is important to get a good combustion or explosion of gases especially in engine or a burner. A smaller spark size with respect to low spark energy or low distance might be resist the spark to occur and therefore will not ignite the combustion. However, a higher spark size or maybe from a high spark energy and high spark gap can sure ignite the combustion easily but might be will easily damage the electrode and easily can affect the system likes the circuit and coil to malfunction due to very high energy or voltage. The larger spark size also might be affected the explosion or combustion in the engine, burner or chamber that can reduced the life of the equipments because of the excess explosion or ignition combustion. Therefore, different spark size needed by different equipment to make the equipment can function properly. From this experiment, the spark size can be determined which can ignite gases that been used. The test of the system had been done towards a bunsen burner which produced a butane gas and from the result, there are some spark energy value can ignite the gas but some are can not. The effect of the spark gap was also been took into consideration when experimenting the ignition of the gas.

Another function that this system can be used is to determine the variation of the spark size during the spark discharge. Kernel radii of equivalent sparks in air atmosphere exhibit a difference as early as 12.5 μs after breakdown. This suggests that kernel growth by chemical energy release occurs very early in the process. The initially rapid growth of the kernel during the spark discharge can be adequately predicted with a mass entrainment term that is a function of the electrical power input. Comparable energy produces about the same size kernels within the time frame of the experimental data suggests a relatively weak dependence of the kernel size on the rate of energy input in the current range. The experiment can be used to predict the effects of spark energy, spark gap, and equivalence ratio on early flame kernel growth with several constants adjusted which is the spark energy and gap at one atmosphere condition.

5.2 Recommendations

The output voltage for the spark ignition system were calculated based on Paschen' Law and therefore it affected by other factor such as the room temperature, pressure, gases and others. Therefore, it is much preferable to use high voltage probe meter to exactly measure the output voltage produced through the spark. High voltage probe meter is one of multimeter or voltmeter that can measure up to 20 to 25 kV of voltage. Therefore, as what had been calculated from the experiment, the highest output voltage produced was around 24 kV. As a result, the high voltage probe surely can support the system to measure the high output voltage correctly.

Furthermore, the variation of energy from this experiment was done by measuring the spark size at a certain period of time. It is much preferable to add an oscilloscope to see the variation of power and current vs time based on the spark size at the certain time and therefore, the exact value of the size at the exact energy can be determined. However, this experiment can not be done like the proposed action above due to absence of potential transformer. Potential transformer is a step down transformer to step down the voltage for example from 20 kV to 20 V and it is measured by the ratio of step down based on number of coil for the primary and secondary.

REFERENCES

ASTM E582-07, "Standard test method for minimum ignition energy and quenching distance in gaseous mixtures," American Society for Testing and Materials (ASTM), West Conshohocken, PA, USA, 2007.

Babrauskas, V. (2003): Ignition Handbook, Published by Fire Science Publishers, A division of Fire Science and Technology Inc., Issaquad, WA 98027, USA.

Basili R, Victor (June 2003), Craig Larman, "Iterative and Incremental Development: A brief history", Computer, Vol. 36, No. 6. (June 2003), pp. 47-56

Blanc, M. V., P. G. Guest, G. von Elbe, and B. Lewis (1947). Ignition of explosive gas mixtures by electric sparks: I. minimum ignition energies and quenching distances of mixtures of methane, oxygen and inert gases. *J. Phys. Chem. 15*, 798--802.

Crouch, K. (1994). Aircraft fuel system lightning protection design and qualifications test procedures development. Technical Report LT-94-1067, Lightning Technologies, Inc.

Dixon, Lloyd H, *Magnetics Design Handbook, Section 5, Inductor and Flyback Transformer Design*, Texas Instruments, 2001

Eckhoff, R. K. (1970): The energy required for the initiation of explosions in dust clouds by electric sparks, M.Phil. Thesis, University of London.

Eckhoff, R. K. (2005): Explosion Hazards in process industries, 1st edition, Houston, Texas, Gulf Publishing Company. ISBN 0-9765113-4-7

Granta material intelligence, the materials information technology experts.
http://www.grantadesign.com/resources/process/casestudies/sparkplug.htm 2011
(Access on 15th June 2011)

Design of an Explosion Vessel for Centrally Ignited Flame
Rahman Abd, H. and Sulaiman, S. A. (2010)
Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 31750 Tronoh, Perak, Malaysia.

International Union of Pure and Applied Chemistry (IUPAC)
Analytical Chemistry Division-analytical compendium Cha10sec313,
Compendium of analytical nomenclature, The Orange Book – 3rd Edition
Inszedy, J., Lengyel, T. and Ure A.M.,
Blackwell Science, 2007 [ISBN 0-632-05127-2]

Kono, M., Kumagai and Sakai, T. (1976): The optimum condition for ignition of gases by composite sparks, Proc. 16th Symposium (international) on combustion, pp. 757-766, The Combustion Institute, Pittsburgh, USA.

Kuchta, J. M. (1985). Investigation of fire and explosion accidents in the chemical, mining, and fuel-related industries—a manual. Bulletin 680, U.S. Bureau of Mines.

Lewis, B., von Elbe, G., Combustion Flames and Explosions of Gases, Academic Press, New York, 1951.

Lewis, B., von Elbe, G., Combustion, Flames and Explosions of Gases, second ed., Academic Press, New York, 1961.

Lewis, B., von Elbe, G., Combustion, Flames and Explosions of Gases, third ed., Academic Press, New York, 1987.

Lim, M. T., Anderson, R. W., Arpaci, V. S., Prediction of Spark Kernel Development in Constant Volume Combustion (1987), Combustion and Flame 69:303-316 (1987)

Litchfield, E.L, Hay M.H., Kubala T.A and Monroe J.S. (1967): Minimum ignition energy and quenching distance in gaseous mixtures, U.S Bureau of Mines Report of Investigation no. 7009.

Magison, E. (1978). *Electrical Instruments in Hazardous Locations* (Third ed.)., pp. 69. The Instrument society of America.

Maly, R. and Vogel, M. (1978): Initiation and propagation of flame fronts in lean CH4-air mixtures by the three modes of ignition spark, in Proc. of 17th Symp. (Internat.) on Combustion: The Combustion Institute, pp. 821-831.

Ngo, M., Determination of The Minimum Ignition Energy (Mie) of Premixed Propane/Air (June 2009), Department of Physics and Technology : [119], University of Bergen, Norway

Omar, A., Mariun, N. and Aris, I.B., Ignition circuit for natural gas ignition system, IEEE the 5th Scored, Malaysia, (Dec. 2007).

Paschen, F. (1889) On the transition to radio in air, hydrogen and carbon dioxide at different pressures required potential difference Annals of Physics 273 (5): 69-75.

Roth, A. J. (1987). Development and evaluation of an airplane fuel tank ullage composition model - volume II: Experimental determination of airplane fuel tank ullage compositions. Technical Report AFWAL-TR-87-2060, Volume II, Air Force Wright Aeronuatical Laboratories, Wright-Patterson Air Force Base, Ohio.

Shepherd, Joseph E., Christopher Krok, J, and Julian J. Lee, California Institute of Technology Pasadena, CA 91125, Explosion Dynamics Laboratory Report FM97-9.

Strid, K.-G. (1973). Experimental techniques for the determination of ignition energy. In *Oxidation and Combustion Reviews*, pp. 1–46.

APPENDICES

Appendix A: Calculations

The calculation of output voltage referring to section 4.4 can be seen below.

Appendix A-1: Calculation for output voltage.

$$V = \frac{(43.6x10^{6}V/(atm.))(1.01325bar \times 1.5x10^{-3}m)}{\ln (1.01325bar \times 1.5x10^{-3}) + 12.8}$$

$$= \frac{66265.55}{6.3108}$$

$$= 10\,500.22 \text{ V}$$

$$= 10.50 \text{ kV}$$

The calculation of Spark energy referring to section 4.5 can be seen below

Appendix A-2: Calculation of ignition energy

$$E = ½ \text{ CU2}$$

$$= ½ (6.8x10^{-12} \times 10500.38^{2}V)$$

$$= ½ (7.4975x10^{-4})$$

$$= 3.7488x10^{-4} \text{ J}$$

$$= 0.37488 \text{ mJ}$$

The calculation of insulation resistance referring to section 4.8 can be seen below Appendix A-3: Calculation of mean average of insulation resistance.

$$\text{Insulation resistance (M}\Omega) = \frac{18.99 + 18.99 + 19.06}{3}$$

$$= 19.01 \text{ M}\Omega$$

The calculation of leakage current referring to section 4.8 can be seen below Appendix A-4: Calculation of leakage current

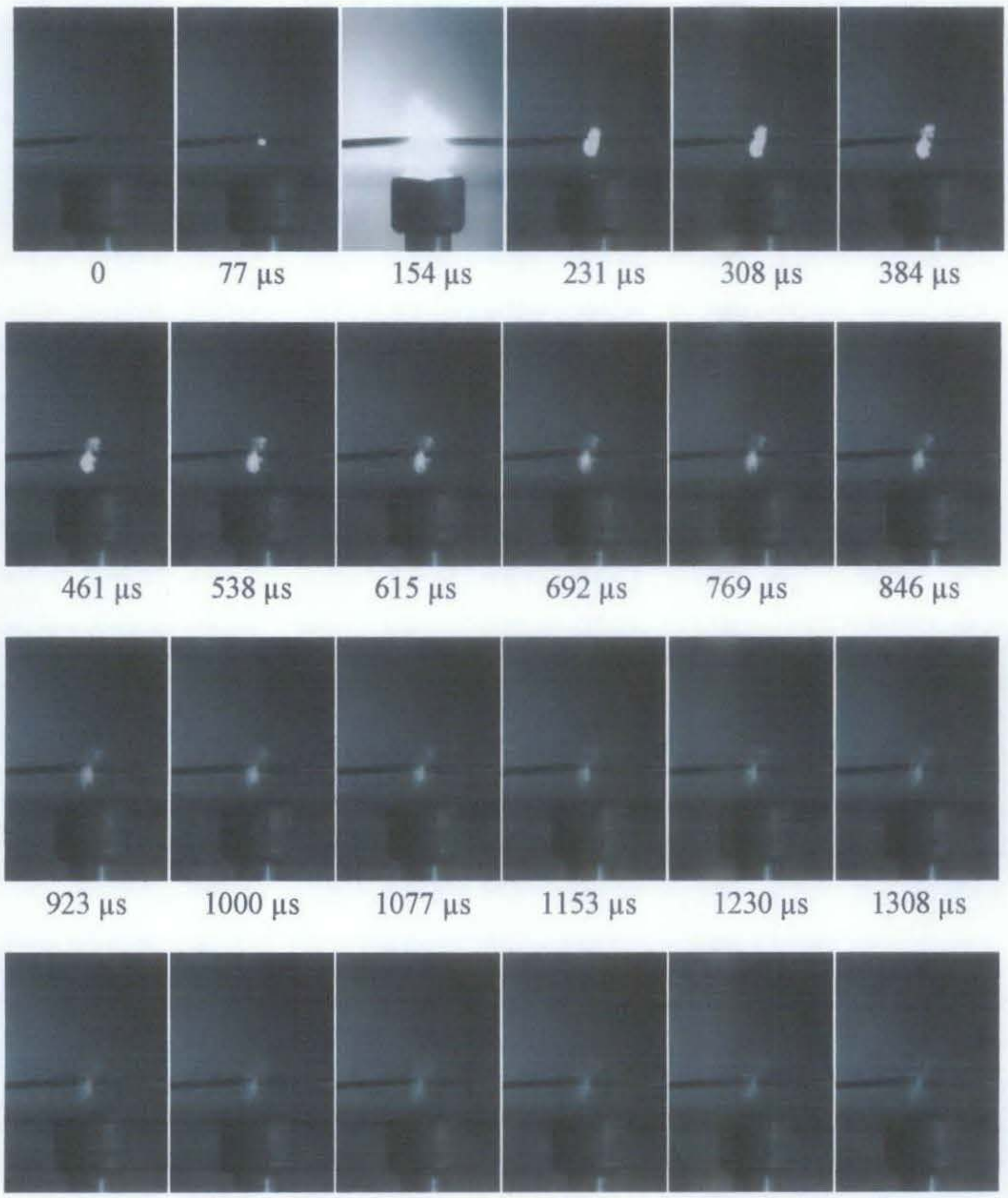
$$\text{Leakage current } (\mu\text{m}) = \frac{\text{Applied voltage (V)}}{\text{Insulation resistance (M}\Omega)}$$

$$= \frac{1000\text{V}}{19.01 \text{ M}\Omega}$$

$$= 52.59 \ \mu\text{A}$$

Appendix B: Ignition of Butane Gas

Flow of figure below is based on ignition system of butane gas that captured by high speed camera in 13000 fps that describe in Section 4.9, igntion by spark.



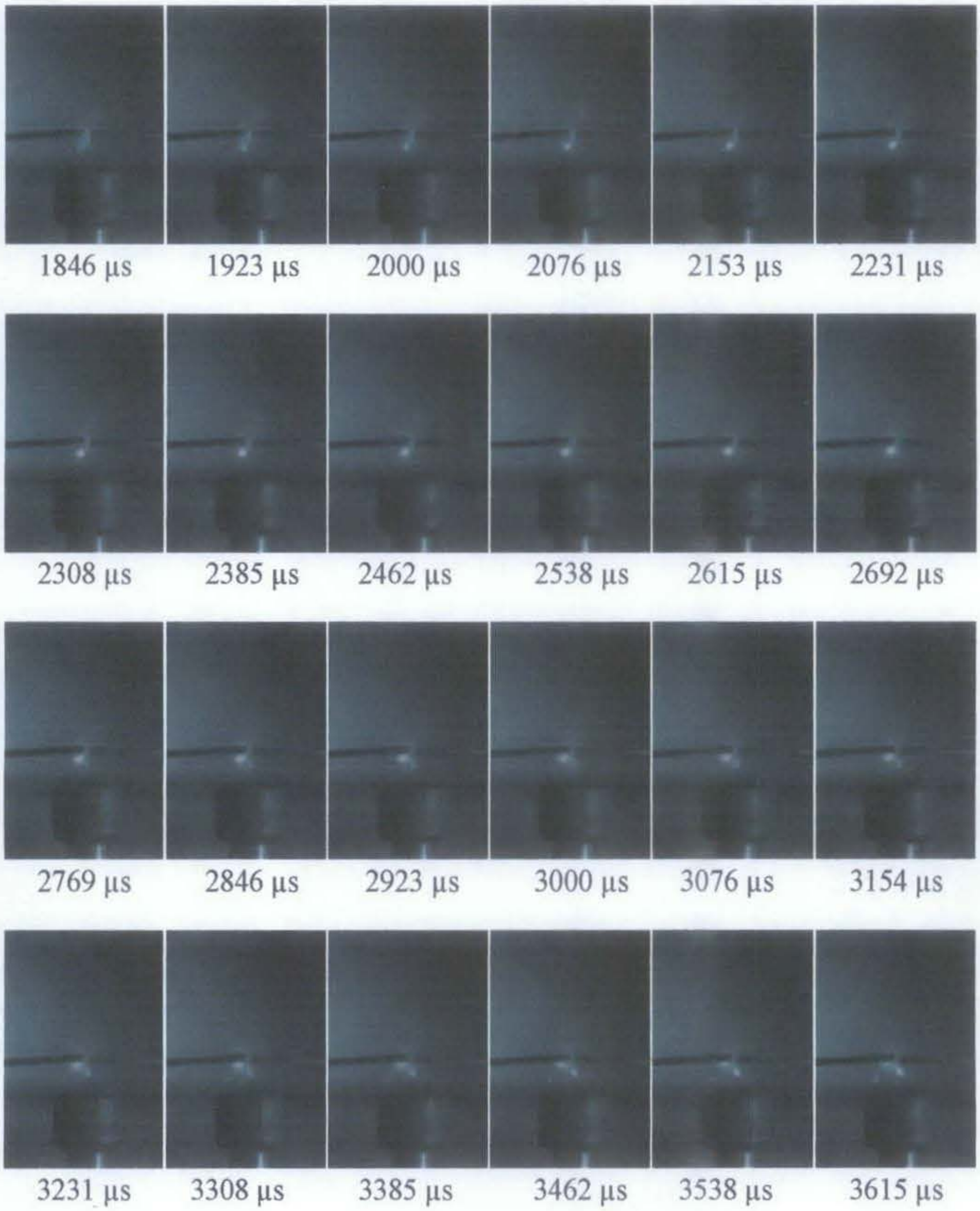


Figure B-1: Ignition of bunsen burner by the spark with 13000 fps