INVESTIGATION ON THE DROPLET COMBUSTION BEHAVIOUR OF PALM BIODIESEL-GRAPHITE OXIDE BLENDS

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A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Honours) Mechanical Engineering

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April 2019

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **“INVESTIGATION ON THE DROPLET COMBUSTION BEHAVIOUR OF PALM BIODIESEL-GRAPHITE OXIDE BLENDS”** was prepared by **LIM PIN JIE** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

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Date : ____________________________________

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ABSTRACT

The toxic emissions from diesel fuel are contributing to the environmental issues such as greenhouse effect and air pollution. Toxic emissions are nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), unburnt hydrocarbons (UHCs) and so on. Blended biodiesel can be an alternative fuel to solve the environmental issues as well as the depletion of fossil fuels. Graphite oxide (GO) is a nanomaterial additive that has high thermal properties that can improves the burning behaviours of pure palm biodiesel (B100). Parts per million (PPM) was used to determine the concentration of GO in B100. Test fuels in this investigation are B100, GO PPM 25, GO PPM 75 and GO PPM 100. This report investigated on the best concentration of GO to blend with B100 based on the droplet burning behaviour. This investigation was carried out with the single droplet combustion experiment. The suspended fuel droplet was ignited by the glow plug and the burning processes were captured. The images of burning fuels were processed by MATLAB to obtain the binary images and areas of the fuel droplets. The changes of droplet area and time taken for burning process were analysed to study the burning behaviour. From the results, GO PPM 75 was shown to have the optimum concentration of GO. It has the highest burn rate constant at 5.3652 mm^2/s. GO PPM 75 has relatively higher amount of bubbling and micro-explosions during the burning process. When compared to B100, the burn rate constant was enhanced by 51.09 %, while the ignition delay and the combustion duration were decreased by 7.69% and 4% respectively. Results showed GO PPM 75 can effectively reduce the emissions and able to improve the fuel efficiency in diesel engine owing to its combustion that is more complete.

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LIST OF SYMBOLS / ABBREVIATIONS

D	Diameter of fuel droplet, mm
D_o	Diameter of initial fuel droplet, mm
k	Burn rate constant, mm^2/s
t	Time taken for the combustion, s

NO_x	Nitrogen oxides
PM	Particulate matter
UHCs	Unburned hydrocarbons
HC	Hydrocarbon
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2O	Water
GO	Graphite oxide
B100	Pure palm biodiesel
PPM	Parts per million
GO PPM 25	1 mg of GO mixed with 40 mℓ of B100
GO PPM 50	2 mg of GO mixed with 40 mℓ of B100
GO PPM 75	3 mg of GO mixed with 40 mℓ of B100
GO PPM 100	4 mg of GO mixed with 40 mℓ of B100
EGR	Exhaust Gas Recirculation
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
SCR	Selective catalytic reduction
LNT	Lean NO_x trap
ID	Ignition delay
CD	Combustion duration
BSFC	brake-specific fuel consumption

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Diesel engine has been widely used in the field of transportation and industry. Diesel engine is used in truck because it produces greater torque and has higher efficiency than the gasoline engine. However, diesel engine contributes to the environmental issues by emitting toxic gasses. The decreasing amount of crude oil and efforts to align with the vision of zero emission around the world, researchers are finding new resources to replace the needs of diesel in diesel engine such as biodiesel.

Biodiesel can be made out of many renewable resources such as waste cooking oil, vegetable oil, Jatropha oil, Karanja oil, palm oil and so on. After comparing the efficiency and productivity of the biodiesel fuels that are made out of palm oil, Jatropha Curcas and the Calophyllum Inophyllum, the best feedstock to make into biodiesel is palm oil (Ong et al., 2011). This is because pure palm biodiesel (B100) has a lower viscosity and it is easier to be ignited. Besides, Malaysia has stable supply of palm oil for the research and development purposes unlike the others possible feedstock. Therefore, B100 is easily produced in Malaysia and it will be used in this study.

Biodiesel is a sustainable energy that will not harm the environment and it comes with a cheaper price in a long run comparing with diesel. Biodiesel will emit lesser of pollutants such as carbon monoxide (CO) and hydrocarbon (HC) but it emits higher concentration of nitrogen oxides (NO_x) compared to diesel. NO_x is harmful to the health of population. There are ways to control the emissions of fuel and they are categorized into pre-combustion treatment techniques and post combustion treatment techniques. Examples of pre-combustion techniques are using additives, applying exhaust gas recirculation (EGR) method, retarding of injection timing and water injection method. Post combustion technique is the application of catalyst (Palash et al., 2013). Fuel modification such as mixing additives into the biodiesel is one of the possible way to reduce the emissions of diesel engine. Fuel modification is cheaper without the need of modifying the structure of diesel engine. Therefore, this investigation will focus in fuel modification on the B100.

Additives that have been used by the past researchers are graphite oxide (GO), cerium oxide, aluminum oxide and carbon nanotube. GO is found to be energetic when it is in mild heating condition (Krishnan et al., 2012). Study regarding of GO in Ooi et al. (2016) also states that it improves the combustion characteristic of diesel better than other additives such as aluminum oxide and cerium oxide. GO shortened the ignition delay of the fuel, improved the burning rate and decreased the burnout time by 46.5%, 29.4% and 13.8% respectively in the study of Ooi et al. (2016). Therefore, GO will be used as the additive in this investigation to improve the burning behavior of B100.

There are not much of studies in finding the effects of the various concentration of the GO mixing with B100. Therefore, this research will be investigating the optimum concentration of GO that is needed to be mixed with the B100 to enhance the burning behavior and lower the emissions B100. The different concentrations of GO that mixed with the B100 in this investigation are GO PPM 25, GO PP 50, GO PPM 75 and GO PPM 100. These test fuels will be comparing to the B100. Single droplet experiment is carried out because the suspended fuel has the similar phenomena of fuel vapor that usually found in the majority of the burning situations in the combustion chamber (Wang, Liu and Law, 1984). Besides, it also requires lower cost to carry out the single droplet experiment without trading off the quality of the experiment data.

1.2 Importance of the Study

Diesel engine has been widely used in the industry of the transportation since the past century and it is still evolving up until today. This leads to the high dependence of crude oil by the industries which causes the crude oil depletes in a very fast pace. Besides, diesel engine emits a lot of pollutants and unfavourable gases such as PM, NO_x, CO, CO_2, UHCs and HC. Therefore, researchers have been working on finding alternative solutions to decrease the dependency of crude oil and to reduce the harmful emissions to the environment. One of the methods is to replace the diesel fuel into biodiesel fuel. Biodiesel has shown a good burning characteristics and it is capable to compete with the efficiency of diesel in the studies from several researchers. Biodiesel will have higher burn rate but longer ignition delay and emits more $NO_{x.}$ More improvements are needed to work on in order to achieve shorter ignition delay and lower level of NO_x emission.

This study will focus in fuel modification where GO was added into B100 as an additive to investigate its burning behaviour. GO is highly flammable and helps to reduce the ignition delay. Its combustion rate is expected to increase too after mixing with the B100.

Single droplet experiment was carried out in this study to investigate the burning behaviour of the test fuels because this creates a good similarity of the droplet fuel during injection in the diesel engine. The burning behaviour of the test fuel also can be studied through the reduction of droplet size during the combustion (Ooi et al., 2017).

The investigated burning behaviours of the test fuels help to determine the efficiency of the Diesel Engine when the particular test fuel is used. When the ignition delay of the test is shorter, the heat needed to ignite the fuel is lower and this reduces the temperature of the cylinder. The lower temperature of burning environment will produce less soot during the combustion. Other than that, the time taken to burn out the test fuel is lesser when it has higher burn rate. This reduces the loss of generated heat into the cylinder wall and increases the efficiency of the engine.

In this study, it is expected to have lower ignition delay and higher burn rate after adding in the GO into B100. This study will find out the optimum concentration of GO to be mixed in the B100. The blend that has a better combustion behaviour can be followed by the better performance of engine with lower emissions.

1.3 Problem Statement

The depletion of crude oil has raised the concerns in finding alternative sources to replace the diesel. Therefore, studies have been widely carried out to investigate the potential of biodiesel as the alternative sustainable fuel.

There are studies showed that biodiesel can compete with the performance of diesel fuel in diesel engine. However, biodiesel fuel emits more pollutants such as $NO_{x,}$ CO and soot than diesel, which is not environment friendly. Therefore, there are several methods to solve the problem and one of them is adding additives to reduce the burning emission. From the study of Ooi et al. (2016), GO has a good reputable as an additive to improve its burning characteristic of fuel. GO performs better than aluminium oxide and cerium oxide nanoparticles as the fuel additive.

In past researches, findings focus in the best type of additives to improve the burning behaviour of the test fuel. GO is the potential additives that shown to be the most effective additive among others. However, there is not much of studies focus in finding the best concentration of a GO in order to have the most effective effects in improving the burning behaviour of the fuel. Therefore, this leads to the investigation of finding the optimum concentration of GO to be blended in B100 that will be carried out in this experiment. The optimum concentration of GO will give the best improvement in the performance of test fuel such as higher burn rate constant, shorter ignition delay and shorter combustion duration compared to B100 that does not have any GO added.

1.4 Aims and Objectives

The main aim of this study was to investigate the droplet combustion behaviour of Palm Biodiesel-Graphite Oxide Blend in the single droplet experiment and obtain the best mixing concentration of GO.

In order to achieve the aim, the specific objectives of this study are defined:

1. To construct the setup of a single droplet experiment to analyse the droplet combustion behaviour of B100 dosed with GO.
2. To investigate the effects of GO on the combustion behaviour of B100 at various dosing concentrations.
3. To compare the droplet combustion performance between the B100 and Palm Biodiesel-Graphite Oxide blends.

1.5 Scope and Limitation of the Study

The working scope of the current study is to find the best concentration of GO in the B100 to produce lower ignition delay, higher burn rate and lesser emission. Adding additives into the biodiesel is one of the way to reduce the emission of engines and improves the burning behaviour of the fuel. Various concentration of GO was mixed with B100 in this study as the test fuels. The test fuels are B100, GO PPM 25, GO PPM 50, GO PPM 75 and GO PPM 100 blends.

In this investigation, the experiment was under the conditions of atmospheric pressure and ambient temperature instead of the temperature and pressure in the combustion chamber of diesel engine. Glow plug was used to aid the auto-ignition of the test fuels. The actual condition of the burning fuel in compression ignition engine was not achieved in this investigation.

The burning process will be captured and imported to MATLAB for analysing the combustion behaviour. A 24 megapixels phone camera was used to capture the combustion process by using the function of burst mode. This is one of the limitation by not having the high-speed camera in the laboratory. Higher frame rate of high-speed camera will be able to capture more data for more detailed results. The study of the emissions of test fuels was based on the chemical characteristics of GO and the burning behaviours of the test fuels.

This study limits in one specific additive only but with different concentrations. GO is the additive in this investigation because it has the good potential as an additive to improve burning behaviour of fuel (Ooi et al., 2017). This investigation will focus in the burning behaviour of fuel droplet only through the single droplet combustion experiment. Therefore, this study does not simulate and take into account of other affecting parameters such as mechanical efficiency of the engine, components of the system and so on. The comparisons in the results of experiment is constricted in comparing among the different concentrations of GO and B100.

1.6 Contribution of the Study

This study investigates on the burning behaviour of the Palm Biodiesel-Graphite Oxide blends by using the single droplet combustion experiment. B100 in this experiment is made out of palm oil because of its large supply in Malaysia. This report may help to convince the market that the palm oil can be put into good use by changing it into a sustainable energy. GO is a thermal active nanomaterial and its properties could contribute in enhancing the burning behaviour of B100. GO can be relatively easier to be obtained compares to other additives in the market by the Hummers Method. The remarkable outcomes of this report may motivates scientists and researchers to put their attention and efforts in GO so that it can produce more sustainable energy products.

The burning behaviours of the test fuel can be obtained in this investigation are the size changes of droplet during burning, ignition delay, burn rate and combustion duration. The enhancement of burning behaviours found in this investigation can theoretically indicates that the fuel will have a greater burning efficiency and able to produce less toxic emissions (NO_x, PM, CO, UHCs) when it is applied in the diesel engine. Moreover, greater burning behaviours of the test fuel will promote the performance of the engine and improve the brake thermal efficiency. This study could show the potential of Palm Biodiesel-Graphite Oxide blend fuel in the field of sustainable energy.

1.7 Outline of the Report

This comprehensive report will be categorised into five chapters. Chapter 1 is the introduction of this investigation. This chapter will explain the concept of this investigation such as the importance of study, problem statement, aims and objectives, scope and limitations of study and contributions of study. After prepping some basic background of study to readers, Chapter 2 will discuss about the works that have been done by other researchers regarding to this study. This section will further discuss on diesel engine, burning characteristics of fuel, existing strategies to improve the performance of diesel engine, biodiesel, additives and experiment setup that are all related to the field of study. In Chapter 3, methodology and work plan of this experiment will be explained to have a better understanding in this experiment procedure. After the data has been collected, the results will be analysed and discussed in Chapter 4. In this Chapter 4, behaviours of droplet, ignition delay, burn rate and combustion duration of the test fuels will be discussed in depth based on the results. Lastly, the report will be concluded in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Diesel Engine

The difference between diesel engine and gasoline engine is their combustion behaviour in the cylinder. Gasoline engine compresses air and fuel vapour in the cylinder and the fuel will be ignited by a spark plug before the piston reaching the top dead centre (TDC). However, the piston in diesel engine only compresses air and the fuel only injected when the piston stroke is near the end. The compressed air is in high temperature condition that will cause ignition to occur when mixed with the fuel. The injection of fuel in diesel engine is crucially important because the control of injection will lead to the efficiency and performance of the engine. Besides, the temperature has to be high enough to allow sufficient heat for the injected fuel to have auto-ignition.

Diesel engine is a highly efficient energy conversion device but it causes environmental issues due to its high toxic emissions. Government has been setting some regulations to restrict the emissions of diesel engines such as Euro 6 (Mohan, Yang and Chou, 2013). The regulations have been stricter recently to force the automotive manufacturers to put effort in improving the efficiency of the diesel engine, as well as reduce the emissions. These restrictions and regulations have pressed the automotive to find strategies to improve the diesel engine.

2.2 Burning Characteristics of Fuel

In the study of the fuel, its burning characteristics can be categorised different in order to have a comprehensive investigation. They are ignition delay, burn rate, micro-explosions and emissions that have been commonly used by researchers to discuss their findings in test fuels. Each of the burning characteristics is due to different factors that will be discussed in this section.

2.2.1 Ignition Delay

It is defined as the time taken in causing the fuel to ignite after being expose to igniter or heat. The delay happens in between the exposure of heat source and the ignition reaction of the fuel (Javed, Baek and Waheed, 2015).

It can be affected by the additives, ambient temperature, and droplet behavior. 2.5% and 5 % of the Nano powders mixed with the heptane fuel droplet will reduce its ignition delay at low temperature but vice versa in high temperature. Javed et al. (2015) concluded that the higher the ambient temperature, the shorter the time delay. Lower ignition delay of the test fuel will result in lesser amount to be burnt. Subsequently, it decreases the formation of NO_x and promotes lower noise level. This helps to solve the problem of high cost in petroleum refineries (Ooi et al., 2017).

From Hoekman and Robbins (2012), ignition delay is highly depending on the cetane number. The report concluded that higher the cetane number available in the fuel, the shorter the time need to ignite the fuel.

2.2.2 Burn Rate

When the fuel has higher burn rate, it will undergo combustion that is more complete. Higher burn rate also known as shorter time taken to complete the combustion process and more complete. Therefore, the heat generated by the fuel would not loss to the cylinder wall when shorter time is taken in combustion. It is favourable for diesel engine to operate by the higher burn rate of fuel.

Burn rate can be affected by the evaporation rate of the fuel. The higher the boiling point the lower the evaporation rate. More time is required to consume the fuel when it has lower evaporation rate (Ooi et al., 2017). Furthermore, burn rate also will be affected by the oxygenate content of the mixture. When the oxygenate content is higher, the burn rate will be increased too due to more oxygen content in it (Zhu, Ma and Zhang, 2013).

Burning rate can be explained under D^2-law. During the combustion, the droplet of the fuel will be reduced and micro-explosion might occurs near the end of the burning state. Micro-explosion that exists in the combustion process can enhance the burn rate. To further study, burn rate constant of the fuel can be determined by plotting the graph of ratio of droplet size against time (Javed, Baek and Waheed, 2015).

2.2.3 Micro-explosion

It is a phenomenon when a droplet of fuel breaks into smaller droplets during the combustion process. This will cause the overall droplet to be completed in burning in a faster rate. The amount of micro-explosion is highly depending on the mixture components of the fuel (Wang, Liu and Law, 1984). The high concentration of fuel trapped within its droplet when it is shrinking is the reason of the occurrence of micro-explosion.

2.2.4 Emission

Soot and NO_x are the main concern in the emission of the diesel engine. The emission amount of high soot is usually high when the fuel is in the high pressure and has turbulent diffusion flames. Besides, the condition of low oxygen concentration and high temperature also promotes the formation of soot in combustion (Mohamed, Kiat and Gan, 2012). The method to investigate the formation soot is usually complex. Therefore, the single-step Khan and Greeves model is used to obtain the required information. This method is less complex and it is carried out by qualitative analysis. Soot is the formation of partially burned products from the premixed combustion. Fuels that are not oxidized cause the formation of soot and usually found in the late phase of combustion.

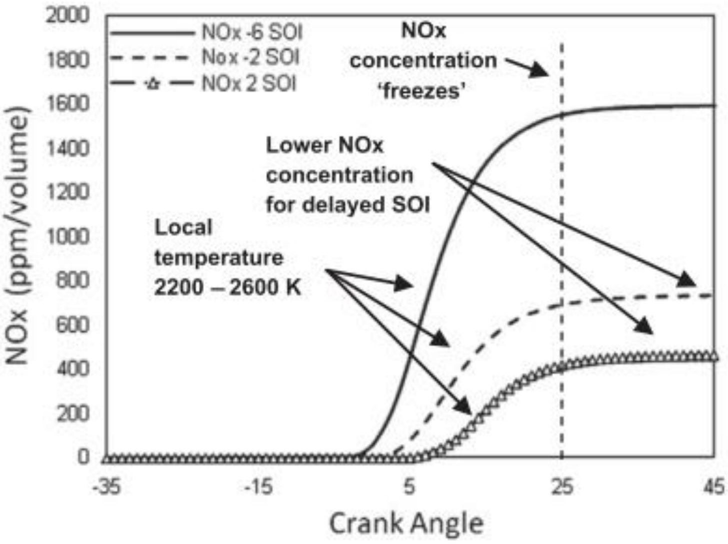


Figure 2.1: Emission of NO_x against Time (Mohamed, Kiat and Gan, 2012).

Hoekman and Robbins (2012) has been discussing about the formation of the toxic pollutant, NO_x from the biodiesel. The formation of NO_x is due to thermal NO_x, prompt NO_x and fuel NO_x. Biodiesel has a higher boiling point compared to diesel as discussed earlier and this leads to high temperature of the in-cylinder and the thermal NO_x. In prompt NO_x, the involvement of hydrocarbon fragments (CH and CH_2) reacts with N_2 during the burning process and produce NO_x. High concentration of hydrogen in the fuel is one of the factor for formation of fuel NO_x. The increase of the concentration of N_2 in the fuel will increase the production of NO_x. Besides, the higher number of cetane in biodiesel causes it to ignite faster when exposed to heat source but it has longer combustion period. This results in the increase of the temperature of cylinder and higher production of NO_x from the burning process. Figure 2.1 shows that the NO_x forms rapidly when the temperature is at the range of 2200K to 2600K. Lastly, high pressure is observed when the fuel is injected and this subsequently increase its temperature and the emission of NO_x (EL-Seesy, Hassan and Ookawara, 2018).

NO_x is the by-product of the hot fuels in the high temperature regions. The emission of NO_x is highly dependent on the temperature of the burning process. However, high temperature will reduce the emission of particulate matters that is harmful to human lungs. Therefore, NO_x and Particulate Matter are not able to reduce in the same time since they are trading off each other. Engine manufacturers have to find the balance in between these two emissions or develop some strategies to overcome it (Mohan, Yang and Chou, 2013).

2.3 Existing Improvement Strategies for Diesel Engine

There a lot of strategies to improve the efficiency of the engine such as Exhaust Gas Recirculation (EGR), exhaust after treatment, engine configurations, higher fuel pressure injection and fuel modification.

2.3.1 Exhaust Gas Recirculation (EGR)

EGR is known as recirculating the cooled exhaust gas and mixing with some fresh intake air into the combustion chamber. The recirculate exhaust gas will not take part in the combustion process. It will substitute some of the oxygen content from the fresh air content. This strategy helps to reduce peak temperature of the combustion chamber and the NO_x emissions will be reduced subsequently. Li et al. (2015) has concluded that the mixture of the air in EGR will change the thermodynamics properties such as gas constant, heat capacity and thermal diffusivity. EGR installation also improved the engine life by lowering the cylinder temperatures specifically the exhaust valve life.

2.3.2 Exhaust Aftertreatment

It helps to achieve lower emission and higher combustion efficiency. In a modern diesel, exhaust aftertreatment devices normally made up of different components namely the diesel oxidation catalyst (DOC), the diesel particulate filter (DPF), selective catalytic reduction (SCR) and lean NO_x trap (LNT).

DOC helps to convert the emission of HC, CO and diesel odour to H_20 and CO_2. However, the concentration of NO_x is not reduced in DOC and this leads to the introduction of SCR and LNT in the system. Xin (2013) reported that the urea-based SCR is known to be more effective compared to LNT. The ammonia generated from urea will be oxidized by the NO_x. The reaction of NO_x and ammonia will produce nitrogen and water. It is crucial to produce a small amount of ammonia for this reaction because excessive of ammonia will cause toxic environment. Therefore, another DOC will be installed after the SCR to solve the problem of excessive ammonia being produced. LNT is performed by exposing to the oxidizing exhaust and the oxidation catalyst will help to reduce the concentration of NO_x.

DPF has high filtration efficiency in filtering the particulates matter and aids in flow restriction. Exhaust restriction can be done by using a back pressure valve. It assists in engine breaking by closing the valve and causes the reduction of exhaust flow. These have the impacts on the performance of engine (Xin, 2013).

2.3.3 Engine Configurations

Automotive technology has been evolving from time to time followed by the design configuration of the engine. The technologies help to improve the engine capacity, its efficiency, compact and fuel economical. The change of engine design is costly but worth the investment in the long run. The change can be implemented on the cylinder bore, the number of strokes, the types of pistons, the types of connecting rods and the cylinder arrangements. These changes will affect the power output of the engine as well as the efficiency of the engine.

2.3.4 Higher Pressure Fuel Injection

The working principle of the diesel engine is by compressing the injected or sprayed fuel in order to gain its energy. The control of fuel injection into the pre-combustion chamber or the piston-cylinder combustion chamber is important. High pressure of injected fuel is favourable because the fuel has sufficient heat to ignite the fuel. Kato et al. (1998) has reported that higher fuel injection pressure helps to reduce the fuel consumption and black smoke. This is due to the lower driving loss when the pressure is high. The engine fuel consumption can also be reduced by reducing the nozzle diameter (Kato et al., 1998).

The high-pressure fuel injection system helps to improve the performance of the engine, as well as reducing the emission levels. Fuel should be injected to the combustion chamber with the effort of minimizing the possibility of wall wetting. Besides, the thermal efficiency of the engine will increase by increasing the injection pressure. Other than that, injection timing technology can be helpful to inject the great pressure of fuel into the combustion chamber to maximize the performance of the engine (Mohan, Yang and Chou, 2013).

2.4 Biodiesel

From Zhu, Ma and Zhang (2013) , it states that biodiesel fuel will take longer time to ignite but it has faster burn rate than the combustion of diesel. Both burning characteristic of diesel and biodiesel can be improved by adding catalyst. Higher burn rate can be due to the higher content of oxygenate which can be found in the biodiesel. Besides, the higher boiling point of biodiesel has a faster burn rate because of its slower evaporation rate.

However, there are another studies showed different results as explained. Ooi et al. (2017) showed that biodisel has a lower burn rate than the diesel which contradicted to the previous statement. The reason given from this research is that biodiesel has higher boiling point that leads to lower evaporation rate. Lesser amount of the fuel can be consumed during the combustion and therefore it requires more time to finish the combustion process.

The combustion of biodiesel does not produce carbon dioxide (CO_2) and sulphur dioxide (SO_2) that would harm the environment. This is because biodiesel is carbon neutral (Suresh, Jawahar and Richard, 2018). Micro-explosions can be found during the linear burning of the blends of biodiesel and additives (Ooi et al., 2017).

Nevertheless, Botero et al. (2012) has concluded that mixing biodiesel into diesel helps to reduce the formation of soot. This is observed through lesser smell of the mixture and oxidizing capabilities of biodiesel. Besides, it also states that castol oil biodiesel has an extra OH function group in its chemical structure in order to reduce the formation of soot more effectively. It has lower burning rate than diesel due to the higher boiling point characteristic.

Furthermore, biodiesel can be made out of many renewable resources such as waste cooking oil, vegetable oil, Jatropha oil, Karanja oil, palm oil and so on. From Nagaraja, Sooryaprakash and Sudhakaran (2015), the best volume concentration of Palm oil mixing with the diesel is 20% based on its performance at compression ratio of 20:1. When comparing it with diesel, the 20% of Palm oil Biodiesel (B20) has 6% higher brake power, lower effective pressure and emits lower temperature of exhaust gas. B20 emits 45.45% lesser amount of C, CO_2 and HC than the diesel. The only high amount of gas emitted by B20 is carbon dioxide, which will deplete the ozone layer, but it is not as harmful as carbon monoxide. B20 performs better in the diesel engine at higher compression ratio. It is convinced that the B20 can replace the diesel base on its better performance and emission result.

There are varieties of the biodiesel fuel available in the studies but B100 that made from palm oil will be chosen as the test fuel in this experiment for further characteristics improvements. This is because Malaysia has a stable supply in palm oil and can obtain palm easily at cheaper price. Therefore, B100 has the potential to substitutes diesel and be a sustainable fuel in the future. Besides, it was studied that B100 has a similar burning characteristic with the diesel especially B20 but has a higher emission of NO_x.

The normal properties of B100 are shown in Table 2.1 as retrieved from MPOB (2019).

Table 2.1: Properties of B100 (MPOB, 2019).

Properties	**Palm Biodiesel**
Ester Content	98.5%
Density at 15 °C	878.3 kg/m^3
Viscosity at 40 °C	4.415 mm^2/s
Flash Point	182 °C
Cetane Number	58.3

2.5 Additives

Different additives will give different effects on the performance of fuel and engine. Each additives serves different purposes such as reducing the emulsion of the fuel, minimizing the clogged engine, improving the burning characteristics of the fuel and so on. In this section will discuss about the additives that can be used as catalyst to improve the burning characteristics of the fuel.

2.5.1 Alcohol

Alcohol can be used as additive to increase its burning rate and decrease the ignition delay. Alcohols that have been studied by researchers to blend with biodiesel are ethanol, propanol, and methanol. The average burning rate is depending on the evaporation rate or vapour pressure of the fuel. The greater it is, the greater the burning rate. Methanol has the highest evaporation rate and causes it to have the longest average burning rate among all.

Micro-explosions phenomena occur in the burning of the binary-component fuels for instance the mixture of alcohol and biodiesel. This can be due to the bubbles induced during injection that causes deformation of shoot shell during the burning. It is found that the increase of the concentration of the alcohol may delays the formation of soot shell. The desired characteristic of the combustion has been improved and achieved with the addition of alcohol in the fuel (Pan and Chiu, 2013). The study also showed that the mixture of 35% of ethanol and 15% of biodiesel helps to loosen the solid structure of soot particles when comparing it to the burning of the diesel droplet.

From Botero et al. (2012), micro-explosions phenomena are observed in the process of burning of ethanol when it is added into diesel and biodiesel. It is favourable to have micro-explosion because it helps to reduce the overall burning time of diesel and biodiesel. Unfortunately, the consumption rate of the fuel will rise too with the increasing of micro-explosion.

2.5.2 Graphite Oxide (GO)

Diesel took 0.8 seconds lesser than the biodiesel to ignite as shown in the result of Ooi et al. (2017). The additional of GO in both of the fuels help to decrease the ignition delay of diesel and biodiesel by 38.2% and 11.5% respectively. The additional oxygen content of GO and its high thermal conductivity contributes to this result. Higher thermal conductivity will lead to higher vaporization of the fuel. Vaporized fuel will bring along the GO to be move away from the droplet. Subsequently, the fuel will ignite sooner because the ignition temperature of GO is lower than the diesel which is 180°C and 250°C respectively.

GO is found to be more effective in diesel. This is due to the lower surface tension of the blend that has weaker attraction between the Diesel and GO that did not obstruct the evaporation process. Besides, the intermolecular forces of nonpolar hydrocarbon diesel also easily weaken by the polar nature of biodiesel and less heat is needed to overcome the bond.

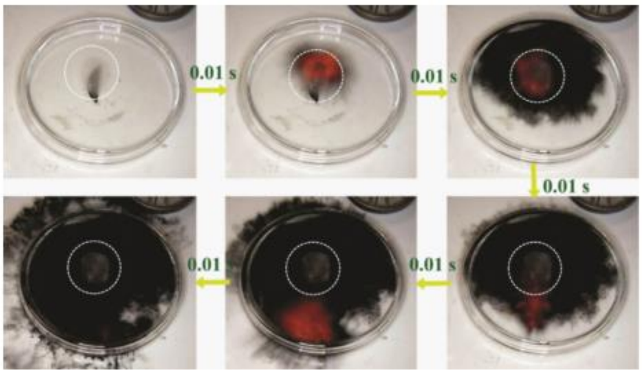


Figure 2.2: Burning Process of GO in a beaker (Krishnan et al., 2012).

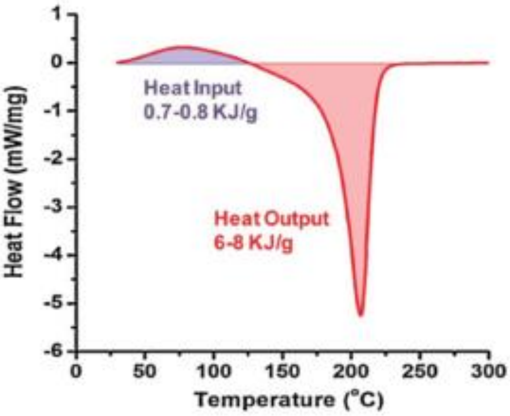


Figure 2.3: Heat Flow of the Burning GO against Temperature (Krishnan et al., 2012).

Figure 2.2 shows an explosion of a piece of GO solid after placing it on the 300°C of reheated hot plate where water vapour formed as circled in white. The heating curve of highly exothermic thermal deoxygenation of GO is illustrated in the heating curve of Figure 2.3. It can be observed that heat output produced by the powders is high at the temperature of roughly 200°C and this definitely contributes to the combustion of its blend fuel. This high output of heat is due to the positive feedback of the energy released and set of a violent explosion as observed in Figure 2.2. The formation of CO_2 and H_2O cause the apparent volume to expand and found that it is more loosely packed. The high specific surface areas in the range of 500—1200m^2/g (Krishnan et al., 2012).

There are studies showed that GO is energetic and thermally unstable. There are some of the factors that shows GO is highly flammable. One of it is that the oxidants, $KMnO_4$ used in the Hummers method is found in the GO that helps to produce oxygen during the combustion. Other than that, water soluble potassium salts that is found in the GO promotes its flammable characteristics. It is a catalyst for GO to be burnt effectively. These potassium compounds are the residue from the filtering process that is hardly to be removed (Krishnan et al., 2012). Therefore, this study shows that the potassium salt can reduce the thermal stability of GO. The production of GO is usually from Hummers Method (Yuan et al., 2016).

From the thesis of Carroll (2016), there are around 50% of oxygen functional group in GO. This helps the test fuel to have a combustion that is more complete. GO can be easily generated from graphite powder which proves to be cost effective. Besides, researchers have been putting extra effort in GO as an effective addictive for the fuel because it is low toxicity compared to metal oxide (EL-Seesy, Hassan and Ookawara, 2018). Moreover, GO provides a large surface area to volume ratio which catalysts more complete combustion process.

It is observed that GO has the functional groups of – OH, –C=O and C=OH from the result of EL-Seesy, Hassan and Ookawara (2018). These functional groups will be bonded with the B100 and provide oxygen compounds for combustion.

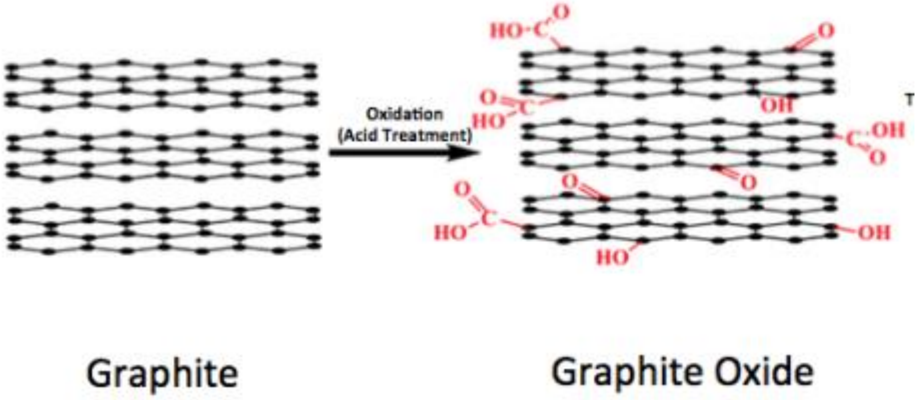


Figure 2.4: Process of Oxidation of Graphite to GO (Carroll, 2016).

Table 2.2: GO Nanoparticle Specifications (Hoseini et al., 2018).

Property	**Value**
Theoretical specific surface area	2630 m^2g^{-1}
Intrinsic mobility	200000 $cm^2V^{-1}s^{-1}$
Young’s modulus	1 TPa
Thermal conductivity	5000 $Wm^{-1}K^{-1}$
Optical transmittance	97.7 %

2.5.3 Cobalt Oxide

Cobalt oxide is also a nanoparticle that can be used as additives in the biodiesel. Study of Mehregan and Moghiman (2018) showed that cobalt oxide reduce more NO_x from the production of burning biodiesel compared to manganese oxide. Nanoparticles have great surface area that helps to decrease the ignition delay. Eventually, this reduces the temperature of burning process and cause lesser amount of NO_x being emitted. This is because the emission of NO_x is proportional to the temperature of the fuel. Addition of the nanoparticles also reduces the carbon monoxide and the exhaust emissions, which are the favourable outcomes.

2.6 Experiment Setup to Study Test Fuels

The model of single droplet combustion experiment is used by several researchers in their finding of the burning behaviour of the test fuels. Single droplet experiment forms a heterogeneous system for the easier investigation on the changes of fuel (Tanabe et al., 1995). The simplicity and similarity of single droplet experiment compared to the combustion chamber enable researchers to produce a comprehensive data of burning behaviour of the test fuels. Javed, Baek and Waheed (2015) showed the method of suspending the single droplet of test fuel is used to ignite the fuel and study the behaviour. The study is mainly focusing in the droplet of the test fuel. The equation of D^2 law is used in this method to study the burn rate of the fuel.

There are several ways to evaluate the burning behaviour of the test fuel. Modelling of spray combustion has been used in the investigation of Stauch, Lipp and Maas (2006). The cost for setting up this model is high because it requires a fast speed camera in order to capture the sprayed droplets. The sprays behave like the gas jet and form a small diameter of test fuel. It is studied by the idealised case instead of the actual burning conditions in the real life that is much more complicated.

Other than that, free droplet technique is also one of the method to study the test fuel behaviour. The fuel droplet will drop into the space of hot furnace by gravitational force to allow the fuel to self-ignite (Williams, 1990).

Williams (1990) stated some assumptions need to be made in the single droplet combustion experiment. Firstly, the droplet is assumed to be in a sphere shape. Next, the thermal diffusions effects are neglected in the experiment analysis. The burning droplet is under the quansi-steady state condition. These assumptions attribute to the graph of squatter diameter against a short time interval based on D^2 law. The burning behaviour of the droplet is linear and less fluctuations in droplet size.

There are studies on the fuel droplet that operates in micro-gravity conditions. This method is required to carry out the experiment under reduced-gravity environment. The fuel droplet in this experiment set up will be in a perfect spherical shape because there is less effect from the gravitational force. This study is suitable in investigating the burning behaviour of the fuel that operates at the outer space such as the use of fuel in engine of spacecraft. This is to study the safety hazards of fuel in micro-gravity condition (Hu et al., 2012).

2.7 Summary

It is important to understand the burning characteristics before analysing the data from the experiment. The burning characteristics such as ignition delay, burn rate, burn duration and its emission are the vital parameters to identify the efficiency of the fuel. In this study, B100 was used as the base fuel and GO acts as an additive was added into the base fuel to study the improvements of burning behaviour. Fuel modification method has a lower costs compared to engine modification, Exhaust Gas Recirculation (EGR) and exhaust after treatment. Single droplet combustion experiment was used to investigate the test fuels due to its ability to illustrate the fuel droplet in the combustion chamber using the assumptions that have been discussed. This experiment has the lower cost of set up without sacrificing the quality of results in burning behaviour of fuel droplet. It is favourable to have a shorter ignition delay, higher burn rate constant, shorter combustion duration and more micro-explosion phenomena to occur in order to produce a greater efficiency of diesel engine as well as lower toxic emissions such as NO_x, PM, CO and UHCs.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This single droplet experiment was carried out because the droplet that underwent in this investigation has high similarity to the fuel particles during the injection of the fuel in fuel chamber of engine. The droplet of the test fuel was suspended and ignited when sufficient of heat was provided to the fuel. The combustion processes were captured and the combustion behaviours of the test fuels were analysed. The combustion characteristics of the test fuels were determined and compared to each other. This investigation is to study the efficiency and emission of the test fuel.

3.2 Fuel Preparation

One of the sustainable energy that can replace the depleting crude oil is biodiesel. There are several studies showed that adding additives into the biodiesel will improve the burning behaviour of the biodiesel. GO has reputable thermal properties in decreasing the ignition delay, increasing the burn rate and shortening the combustion duration of the fuel. Therefore, B100 will be used in this investigation and different concentrations of additives GO were blended with B100. The optimum concentration of GO in B100 was to investigate. The GO was obtained from company Sigma-AldRich (2016) and its specifications are shown in Table 3.1. Meanwhile, the B100 is obtained from company ExcelVite and its specifications are shown in Table 3.2.

Table 3.1: Specifications of GO in this Experiment (Sigma-Aldrich, 2016).

Properties	GO
Edge-oxidized	4-10%
Sheets	15-20
Molecular Weight	4239.48 g/mol
Relative Density	1.8 g/cm^3
Form	Powder
Colour	Black

Table 3.2: Specifications of B100 in this Experiment (ExcelVite, 2015).

Properties	**B100**
Density at 15°C	860 – 900 kg/m^3
Viscosity at 40°C	3.5-5.0 mm^2/s
Cetane Number	51
Flash Point	101 °C

The concentration of GO was calculated based on parts per million (PPM). The value of PPM is suitable to measure the dilute concentration substances. Below shows the calculation of required mass of GO in different concentrations (25 ppm, 50 ppm, 75 ppm, 100 ppm). 1 kg is equivalent to 1000 mℓ. The volume of B100 was fixed at 40 mℓ to ensure the consistency of test specimens.

$$25\text{ppm} = \frac{25\text{mg}}{1\text{kg}} = \frac{25\text{mg}}{1000\text{m}\ell} = \frac{1\text{mg}}{40\text{m}\ell}$$

$$50\text{ppm} = \frac{50\text{mg}}{1\text{kg}} = \frac{50\text{mg}}{1000\text{m}\ell} = \frac{2\text{mg}}{40\text{m}\ell}$$

$$75\text{ppm} = \frac{75\text{mg}}{1\text{kg}} = \frac{75\text{mg}}{1000\text{m}\ell} = \frac{3\text{mg}}{40\text{m}\ell}$$

$$100\text{ppm} = \frac{100\text{mg}}{1\text{kg}} = \frac{100\text{mg}}{1000\text{m}\ell} = \frac{4\text{mg}}{40\text{m}\ell}$$

The test fuels that were used in this investigation are:

1) Pure palm biodiesel (B100)
2) Blend of 1 mg of GO and 40 mℓ of B100 (GO PPM 25)
3) Blend of 2 mg of GO and 40 mℓ of B100 (GO PPM 50)
4) Blend of 3 mg of GO and 40 mℓ of B100 (GO PPM 75)
5) Blend of 4 mg of GO and 40 mℓ of B100 (GO PPM 100)

GO used in the laboratory was grinded finely before mixing with B100 to avoid the cluster of particles. The cluster of GO will affect the results of burning behaviours. Besides, the blends of test fuels are required to process in the sonication machine for 30 minutes to ensure the GO and B100 bends are mixed well. The ultrasonic wave helps to break the GO particles into smaller particles and eases the bonding of two different substances, which it is not achievable by the swirling action.

3.3 Experimental Setup

The single droplet combustion experiment has been adopted to investigate the burning behaviour of the test fuels. The schematic diagram of the single droplet experiment setup in this experiment is illustrated in Figure 3.1 and Figure 3.2 by their top view and side view respectively.

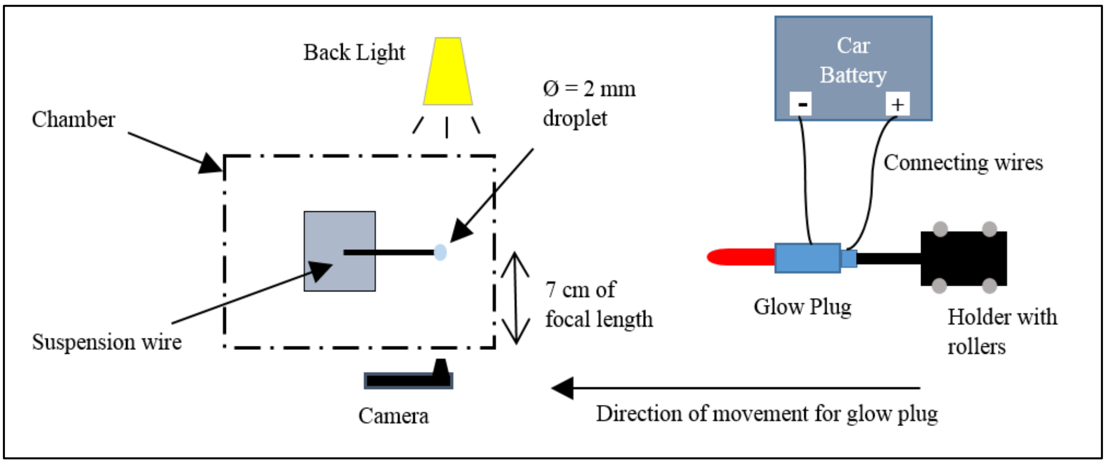


Figure 3.1: Schematic Diagram of the Single Droplet Experiment Setup (Top View).

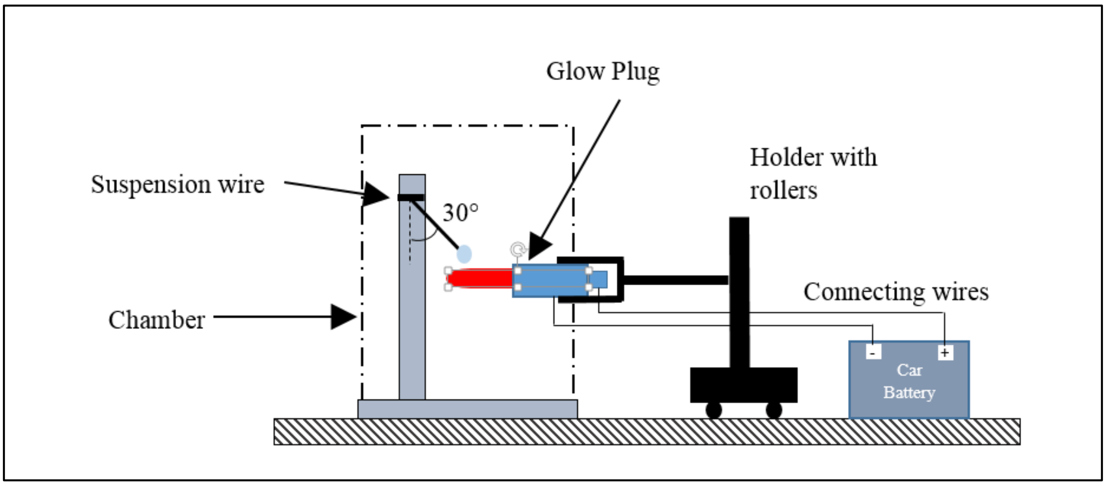


Figure 3.2: Schematic Diagram of the Single Droplet Experiment Setup (Side View).

The fuel droplet was suspended on a wire for the combustion to take place. The wire will be tilted at 30° from the vertical plane. This is the best angle to suspend the droplet. If the angle of the wire is too low, it will be hard to suspend the droplet due to lesser of droplet surface can be hold by the wire. Whereas the angle of wire is tilted to be greater than 30°, the suspended droplet will be in the shape of ellipse. This is due to greater droplet surface is in contact with wire. Therefore, it was found that the best angle for the wire is 30° because the droplet can be easily suspended and will be in a shape that is near to sphere. A syringe was used to suspend a 2 mm of droplet diameter at the tip of the wire.

Heating component that was used in this setup is glow plug. Glow plug is designed to heat up the diesel fuel in the combustion chamber of the diesel engine. Therefore, glow plug is the perfect match in this experiment in order to illustrate a similar environment as in the combustion chamber of diesel engine. Glow plug was heated up by the car battery in this setup. Glow plug has to be connected correctly according to the terminal of car battery in order to heat up. The plug body of the glow plug that comes with thread surface was connected to the positive terminal of the battery, while the end connector of the glow plug was connected to the negative terminal of the battery as illustrated in the schematic diagram. The glow plug was hold firmly by an adjustable gripper and it was designed with rollers at the bottom of the holder. The gripper was set at a fix height and the rollers were assisting the movement of glow plug in a straight line. Glow plug was required to move near to the fuel droplet for the auto ignition to occur and move out once the ignition took place. Therefore, this holder eased the movement of glow plug and provided a consistency of movement.

Chamber in this setup helps to control the surrounding environment of the burning droplet. Surrounding wind and pressure can be blocked by the chamber during the burning process. These will affect the burning behaviour of the droplet and accuracy of the data. Chamber also contributed as heat trap in this experiment setup.

A 40 W LED Bulb was used to provide the back light. Back lighting was provided at the background of the fuel droplet to create the better quality of monochrome image. The fuel droplet could be observed easily during the combustion period through this back lighting method.

The burning processes of the test fuels were captured by a 24 megapixels camera. The distance between the camera lens to the fuel droplet was 7 cm because it is the shortest focal length for the camera. The camera has to be positioned at the nearest as possible for a clearer picture. The monochrome images with the resolution of 5632 × 4224 were captured. These images were processed by MATLAB to transform into binary images. MATLAB image processing function is suitable for calculating the area of an irregular shape such as the fuel droplet that is not in a perfect sphere.

3.4 Data Conversions

The area of the images obtained in MATLAB has the unit of pixels$^{2.}$ Meanwhile, the unit of diameter that is needed in D^2 Law is in mm. Therefore, it requires some calculations to convert the unit of area from pixel to mm.

The computer that was used to run the MATLAB program is in 96 dpi (dots per inch). This means that the monitor is able to display 96 pixels per inch. The 96 dpi indicates that one pixel is equal to 0.264583333 mm. The diameter of the droplet can be obtained by using Equation 3.1. A ratio method has been adopted to obtain the actual diameter of the droplet as shown in Equation 3.2. This conversion method is implemented in order to plot the graph as shown in Figure 4.6.

$$\mathrm{D} = \sqrt{\frac{4\times\mathrm{A}}{\pi}} \tag{3.1}$$

Where,

D = Diameter of the test fuel, pixel or mm

A = Area of the test fuel, pixels^2 or mm^2

$$\frac{\mathrm{D_{actual}}}{\mathrm{D_{actual(initial)}}} = \frac{\mathrm{D_{matlab}}}{\mathrm{D_{matlab(initial)}}} \tag{3.2}$$

Where,

$\mathrm{D_{actual}}$ = The actual fuel diameter at particular burning time, mm

$\mathrm{D_{actual(initial)}}$ = The actual initial fuel diameter, which is fixed at 2 mm

$\mathrm{D_{matlab}}$ = The fuel diameter converted from pixel at particular burning time, mm

$\mathrm{D_{matlab(initial)}}$ = The initial fuel diameter converted from pixel at particular time, mm

3.5 Procedure of the Experiment

After the blends of the test fuels were prepared and the experiment setup was constructed, there are several steps to retrieve the data of the burning behaviours of the test fuels in this experiment setup. The experiment is carried out based on the flow chart that is illustrated in Figure 3.3. Firstly, a droplet of the test fuel is suspended at the tip of the syringe. A 25 mℓ syringe is used to ensure the diameter of the suspended test fuel is 2 mm because it is easier to control the fuel output by smaller syringe. Next, the constructed chamber is used to cover the surrounding of the droplet. The back light is turned on and the camera is in a ready position for capturing. After that, the glow plug is heated up by connecting it to the battery. Once the glow plug shows burning red at its tip, the glow plug holder is pushed forward to bring the glow plug near to the suspended fuel. The heated up glow plug is placed below the droplet of the test fuel. Camera starts to capture the images of test fuel when the droplet is exposed to the heat from glow plug. The glow plug has to be rolled out from the chamber once the droplet is ignited. The camera continues to capture the burning process until he test fuel is fully extinguished. The above steps are repeated for 3 times for each test fuels to obtain the average data.

In between of each repeating steps of the test fuels, there are several things to ensure the accuracy of data. Different syringes are used for the different concentrations of test fuels to avoid any mixture between the different blends. The tip of the wire is cleaned before suspending the other droplet of the test fuel to make sure there is no residue from the previous burning process. The glow plug must be near to the fuel droplet but the glow plug should not in contact with it.

The captured monochrome images are processed by using MATLAB to obtain the areas of the droplets across the burning time. The data obtained from the MATLAB is further analysed to investigate the burning behaviours of each test fuels. The time interval between each images is 0.07 seconds. Therefore, the ignition delay and combustion duration of the test fuels are obtained by observing the burning process through images. Next, D^2 law is used to obtain the burn rate constant of the test fuels.

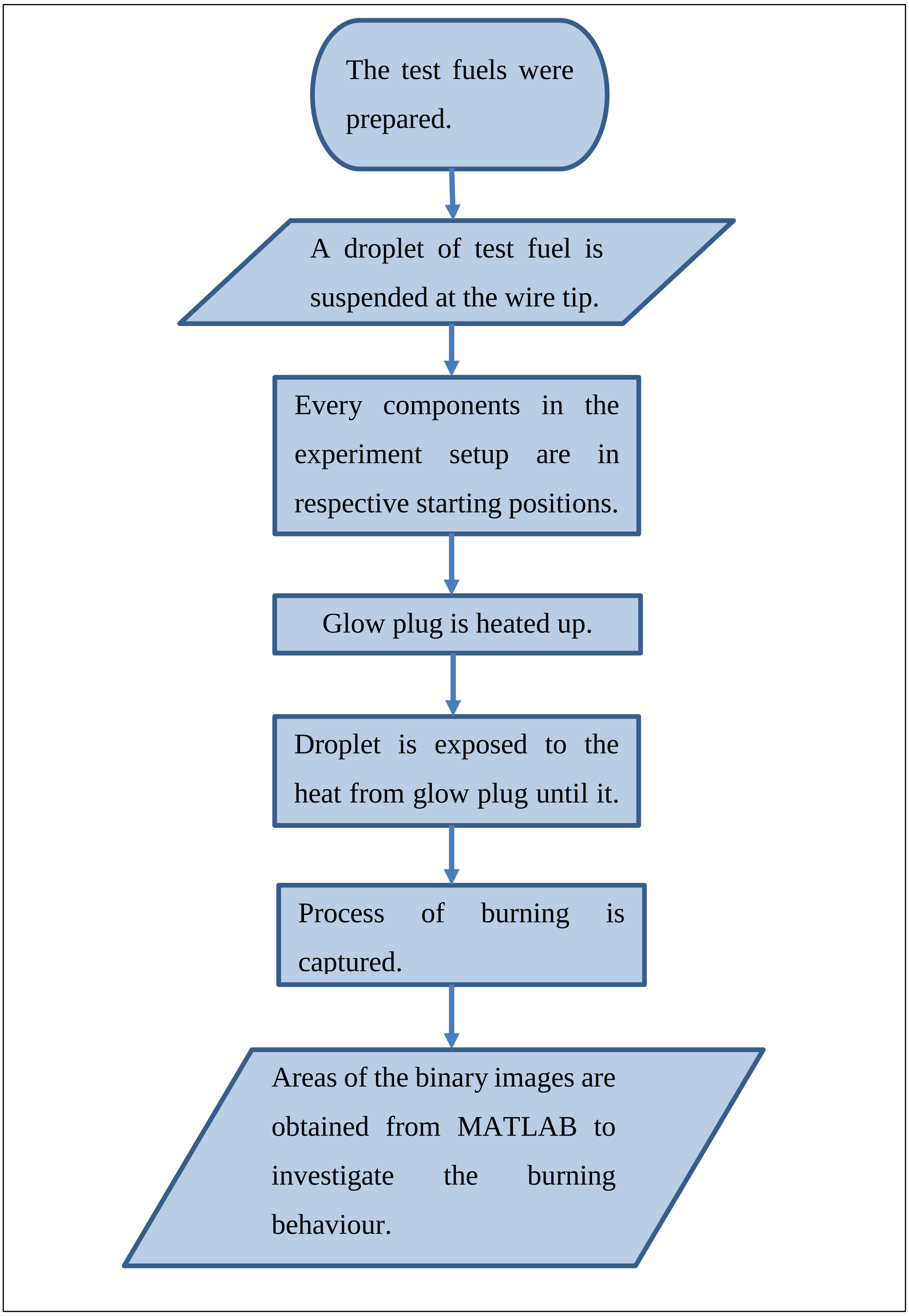


Figure 3.3: Flow Chart of the Single Droplet Combustion Experiment.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The efforts of looking for alternative energies have been rising in order to solve the issues of depleting crude oils. Besides, the stricter regulations and laws enforced to the automotive industry push the researchers to find alternative strategies in improving the fuel efficiency and lower emissions of the fuel. For instance, the Euro 6 regulation was implemented in September 2015 that allows emission level of NO_x for diesels engine to be at 80 mg/km only. It is suggested that adding the additive GO in B100 can increases the burning behaviours of fuel and has lower fuel emissions. Single droplet combustion experiment was carried out to study the burning behaviour and the effects of GO in B100. The burning behaviour of the test fuels can be used to determine the fuel emissions and performance of engine.

There are several studies showed the improvement in the performance of burning when GO was added into the test fuels. For example, Ooi et al. (2018) showed the addition of GO into the diesel will cause overall greater combustion, performance and lower emissions. Therefore, B100 was used in this research to investigate whether the GO additive will have the similar trend in improving the burning behaviour of B100. Different concentrations of GO were added into B100 for investigation.

4.2 Behaviour of Droplet

The graph of Normalised Area against time of the burning test fuel is used to study the changes of the fuel droplet’s behaviour. Normalised area is calculated in the ratio of current area to its initial area. This is to have a better comparison among all of the different test fuels. The normalised areas of the test fuels are shown in Figure 4.1 are to illustrate their burning behaviour. The trend of the droplets in this experiment is agreed by the results from Ooi et al. (2016). The burning behaviour can be separated into three different stages for the analysis purposes. They are preheating stage, steady burning stage and unsteady burning stage that are observed in this experiment.

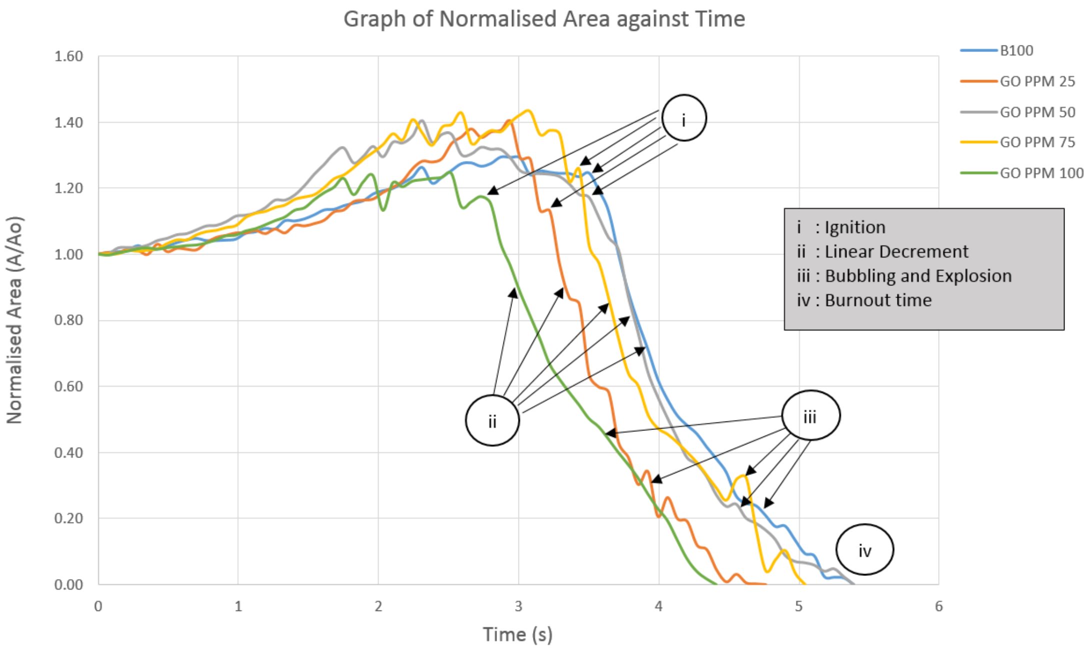


Figure 4.1: Normalised Droplet Area against Time for the Test Fuels.

Preheating stage is the phenomena whereby the droplet is absorbing the heat for ignition. It can be observed from Figure 4.1 that there is an overall trend of fluctuating in the size of the fuel droplet before the test fuel ignites. When the value of normalised area is greater than one, this indicates that the size of the droplet is expanding due to the absorption of the heat. The droplet was trying to overcome its surface tension by absorbing the heat. The droplet was receiving heat in order to have sufficient heat energy to ignite the fuel.

From graph in Figure 4.1, it is observed that B100 test fuel has the least obvious trend of fluctuations in size compared to the blended fuel with GO. This is because B100 test fuel mainly consists of the palm fatty acid methyl ester. This caused B100 to have a higher kinetic viscosity and will not be efficient in fuel-air mixing and lower evaporation rate (E et al., 2016). This is the reason why cavities are less likely to occur in B100 droplet.

GO PPM 75 has the most obvious fluctuations trend in the pre-heating stage of this experiment. This is due to the radiation absorptivity of the test fuel is increased with the presence of GO (Tanvir and Qiao, 2016). Meanwhile, Tanvir and Qiao (2016) also stated that the penetration depth of the absorbed heat radiation decreases when the concentration of the nanoparticles increases. Therefore, it requires more time and heat for the droplet to overcome the surface tension. GO PPM 75 can absorb the heat actively to overcome its high surface tension and this explains the highly fluctuations of GO PPM 75 droplet. The high energy absorbed by the GO PPM 75 will help the fuel to burn at fast pace after it was ignited.

Furthermore, it can be observed from the graph that all the test fuels will have high peak of curve due to a rapid expansion of the droplet size as the particles of the fuel droplets were in their highest excitation state. These phenomena usually take place when the fuel droplet ignites after sufficient of heat is absorbed. It also shows that the test fuel has achieved its auto-ignition temperature.

When the value of the normalised area is smaller than value of one, this indicates that the area of the fuel droplet has been decreased compared to its initial diameter. Based on Figure 4.1, it can be observed that the size of the droplet was decreasing gradually after a sharp expansion of size. This downline trend can be classified into steady burning stage and unsteady burning stage.

During the stage of steady burning, the curve will have a trend of linear decrement and less fluctuation in size. Therefore, the burn rate constant can be calculated at this stage based on the D^2 Law. Burn rate constant will be further discussed at Chapter 4.4. The steady burning phenomenon will end with micro-explosions of the droplet as reported by Ooi et al. (2016). This phenomenon usually occurs during the combustion of colloidal droplet as mentioned in the report of Ghamari and Ratner (2017). Colloidal droplet is chemically defined as a mixture of dispersed insoluble particles suspended in a substance. The blends of GO and B100 in this experiment will produce colloidal droplet or known as multicomponent droplet. In the burning of multicomponent droplet, the base fuel B100 will burn first due to its higher volatility and the nanoparticles GO tends to agglomerate at the centre of the droplet and lesser amount of GO will be at the droplet surface. This explains the occurrence of strong micro-explosions at the end stage compared to the weaker micro-explosions observed at the beginning of burning. It is desired to have greater amount of micro-explosion to occur in order to reduce the required time for combustion in diesel engine. The different boiling points of the components in the blend fuel also cause the instability in the size of the fuel.

In the steady burning stage, GO PPM 25 has shown to have the most obvious of size fluctuations among the test fuels as observed in Figure 4.1. It is believed that the presence of GO in the test fuels caused the disruption and micro-explosions. Cavities formed in the droplet of GO PPM 25 are observed as shown in Figure 4.2

during the combustion process that causes fluctuations in size. Formations of cavities increase the probability of micro-explosions due to greater exposure of the test fuel to air. The fluctuations of size are due to the high occurrences of bubbling and micro-explosions in GO PPM 25 during the linear burning stage. However, it helps to reduce the overall burning duration of the test fuel.

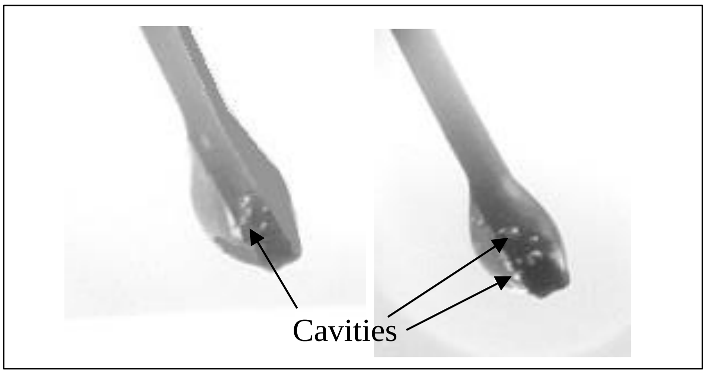


Figure 4.2: Cavities Formed in the Droplet of GO PPM 25.

Lastly, the relatively sharper fluctuations in size are shown in the unsteady stage due to bubbling and disruption behaviour of the fuel droplet. GO PPM 75 and GO PPM 25 showed an obvious unsteady trend comparing with others. A huge increase in the droplet size can be observed. This is due to the merging of cavities in the fuel droplet to form a large bubble in the droplet. A big bubble can be found in the droplet of GO PPM 25 as shown in Figure 4.3. The bubbles will be exploded and it is known as micro-explosions that resulted in a big reduction in size. The burning process will be ended with a visible smoke as shown in Figure 4.4. GO PPM 75 has the second shortest of the overall combustion duration among the blended test fuels. This can be explained by the phenomena of bubbling and micro-explosions too but it is lesser than GO PPM 25.

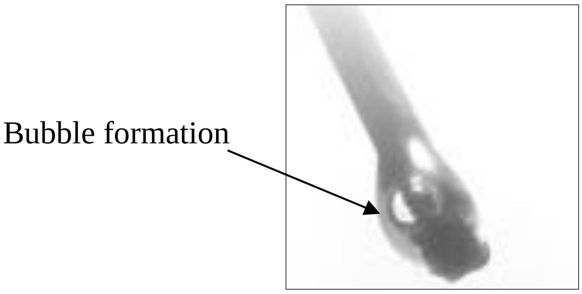


Figure 4.3: Appearance of Bubble in GO PPM 25 Fuel at the Unsteady Stage.

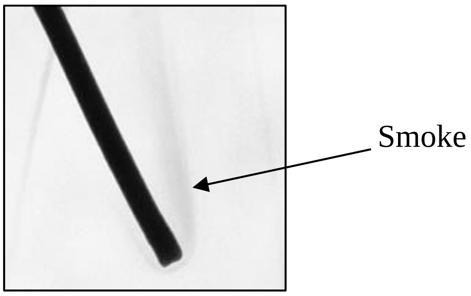


Figure 4.4: Visible Smokes at the end of Combustion.

The trend of changing droplet size during the burning process that plotted in Figure 4.1 can be observed from the captured images. The observations of all the test fuels have been tabulated in Table 4.1, Table 4.2, Table 4.3, Table 4.4 and Table 4.5. Overall, the droplet of the test fuel increases in size at the beginning stage and decrease after ignition takes place. Cavities are found in the droplets that cause the fluctuations in droplet size.

Table 4.1: Combustion Behaviour of B100 at Different Stages.

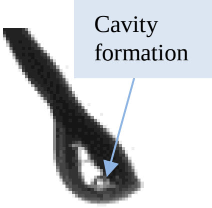
B100	**(a)Initial droplet size**	**(b) Before Ignition**	**(c) After Ignition**	**(d) During Combustion**	**(e) End of combustion**
Time	0	2.1 s	3.71 s	4.41 s	5.39 s
Monochrome images					
Binary Images					

Table 4.2: Combustion Behaviour of GO PPM 25 at Different Stages.

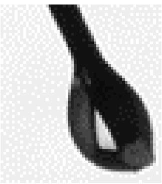
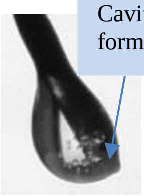
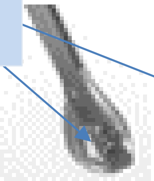
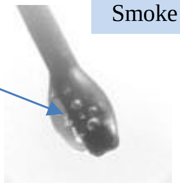
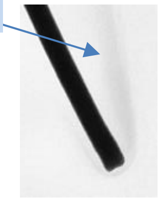
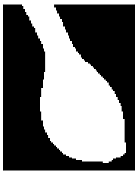
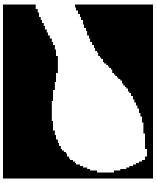
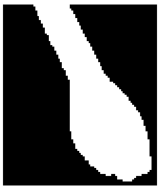
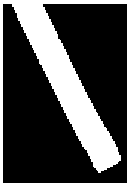
GO PPM 25	**(a)Initial droplet size**	**(b) Before Ignition**	**(c) After Ignition**	**(d) During Combustion**	**(e) End of combustion**
Time	0	2.03 s	3.29 s	4.06 s	4.76 s
Monochrome images		 Cavities formation		 Smoke	
Binary Images					

Table 4.3: Combustion Behaviour of GO PPM 50 at Different Stages.

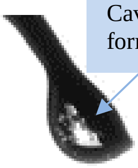
GO PPM 50	**(a)Initial droplet size**	**(b) Before Ignition**	**(c) After Ignition**	**(d) During Combustion**	**(e) End of combustion**
Time	0	2.1 s	3.85 s	4.55 s	5.11 s
Monochrome images		 Cavities formation			 Smoke
Binary Images					

Table 4.4: Combustion Behaviour of GO PPM 75 at Different Stages.

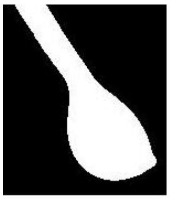
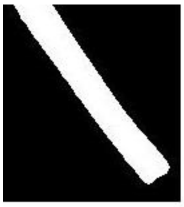
GO PPM 75	**(a)Initial droplet size**	**(b) Before Ignition**	**(c) After Ignition**	**(d) During Combustion**	**(e) End of combustion**
Time	0	2.31 s	3.50 s	4.48 s	5.04 s
Monochrome images					
Binary Images					

Table 4.5: Combustion Behaviour of GO PPM 100 at Different Stages.

GO PPM 100	**(a)Initial droplet size**	**(b) Before Ignition**	**(c) After Ignition**	**(d) During Combustion**	**(e) End of combustion**
Time	0	1.54 s	3.01 s	3.43 s	4.41 s
Monochrome images					
Binary Images					

4.3 Ignition Delay

Ignition Delay is the time needed for the fuel droplet to be ignited from its original droplet state (EL-Seesy, Hassan and Ookawara, 2018). The time taken for the ignition delay will be starting from the test fuel receiving heat to its ignition where the flame is produced. The droplet will be ignited once it receives sufficient of heat from the glow plug. In this experiment setup, the glow plug was placed near to the droplet but was not in contact to maximise the heat transfer for ignition to take place. The consistency of the gap between the droplet and the heat source is important for a better comparison among the test fuels.

The ignition delays of the test fuels in this experiment have been tabulated in the bar chart as shown in Figure 4.5. It is observed that the Ignition Delay of the B100 and GO PPM 50 test fuels have the same Ignition Delay at 3.64 seconds but others have an obvious decrease in their Ignition Delay. This is due to the additional of GO additives that increases the cetane number in the test fuel. Greater amount of cetane numbers improve the evaporation rate of the test fuel and lesser heat is required to ignite the fuel. These results are in agreement with EL-Seesy, Hassan and Ookawara (2018). It is reported that cetane number of the test fuels directly enhances the ignition quality of the fuels. The additional of the high thermal conductivity of GO in the test fuel increases its cetane number and its evaporation rate.

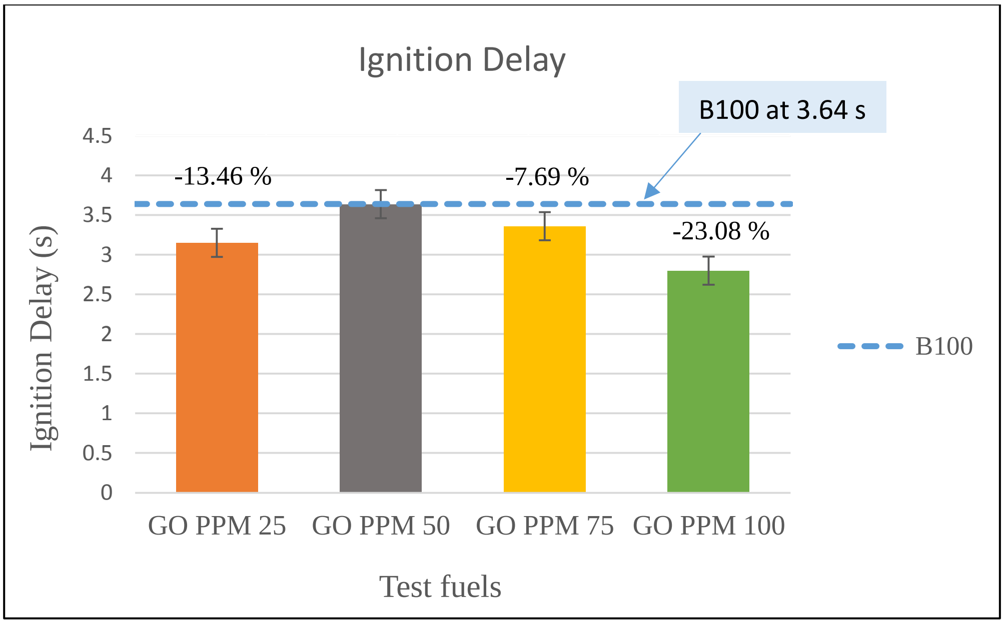


Figure 4.5: Ignition Delay of the Test Fuels.

Besides, the reduction of ignition delay is due to the increase of the oxygen concentration of the test fuels. Various oxygen functional group is found in GO as mentioned in Ooi et al. (2017). GO provides oxygen molecules to catalyse the combustion reactions. From Figure 4.5, the linear decrement of ignition delay from GO PPM 50, PPM 75 to PPM 100 are observed and this is due to the increase of oxygen contain and the cetane number when the concentration of GO is increased. This leads to the GO PPM 100 has the shortest ignition delay among the test fuels at 2.8 seconds by having 23.08% of percentage reduction compared to B100.

GO PPM 25 has the shorter ignition delay compared to GO PPM 50 which contradicts to the discussion earlier. The lesser amount of GO in the blend will result in lesser chemical bond in between the B100 and GO. This causes less heat is needed to overcome the bond during the pre-heating stage. Therefore, the percentage reduction of GO PPM 25 is 6.25% when compared to GO PPM 75. Overall, the blends with presence of GO additives decrease the ignition delay of B100.

It is desirable to obtain a shorter ignition delay fuel because lower temperature is needed to ignite the flame. Hence, lesser amount of NO_x will be formed due to lower flame temperature. Fuel that has shorter ignition delay can lead to lower combustion noise, engine noise and exhaust emissions as mentioned in Najafi (2018). Nevertheless, the increase of cetane number also cause the reduction of CO, PM and UHC emission, but increases the emission of NO_x based on the report from Chukwuezie (2017) and Hoseini (2018). The high cetane number can improve the engine performance by reducing the brake-specific fuel consumption (BSFC) and increase the thermal brake efficiency (EL-Seesy, Hassan and Ookawara, 2018).

4.4 Burn Rate

Burn Rate can be obtained by analysing the droplet diameter in its linear burning condition. MATLAB image processing was used to obtain the diameter of the droplets across the burning process. The changes of diameter were then observed and analysed to understand the burning behaviour of the test fuel. Tanvir and Qiao (2016) reported that when the concentration of the nanoparticles increases, the mean distance between the particles will reduce and cause the collisions and aggregations of the particles to be more frequent. Therefore, less time is needed for the combustion process and having a more complete combustion in the combustion chamber.

It was observed from Figure 4.6 that the diameter squared of the fuel droplets decrease linearly during the combustion, which follows the classical D^2-law. Equation 4.1 was used to study the D^2-law. The unsteady burning behaviour should be isolated and only assume the linear burning behaviour of the fuel in this equation.

$$D^2 = D_0^2 - kt \tag{4.1}$$

Where

D = Diameter of the fuel droplet at t, mm

D_o = Initial diameter of the fuel droplet, mm

t = Linear burning time, s

k = Burn rate constant, mm^2/s

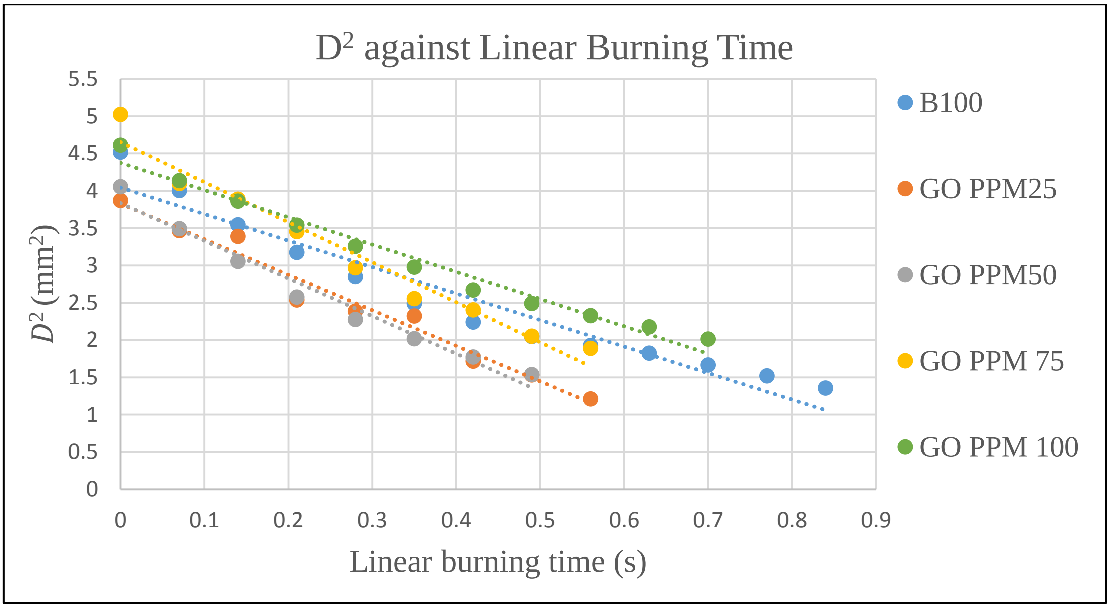


Figure 4.6: Diameter Squared against Linear Burning Time for the Test Fuels.

The burn rate constant of the test fuels can be obtained from the gradient of the line in Graph of D^2 against linear burning time. It is tabulated in Figure 4.7 to have a better comparison.

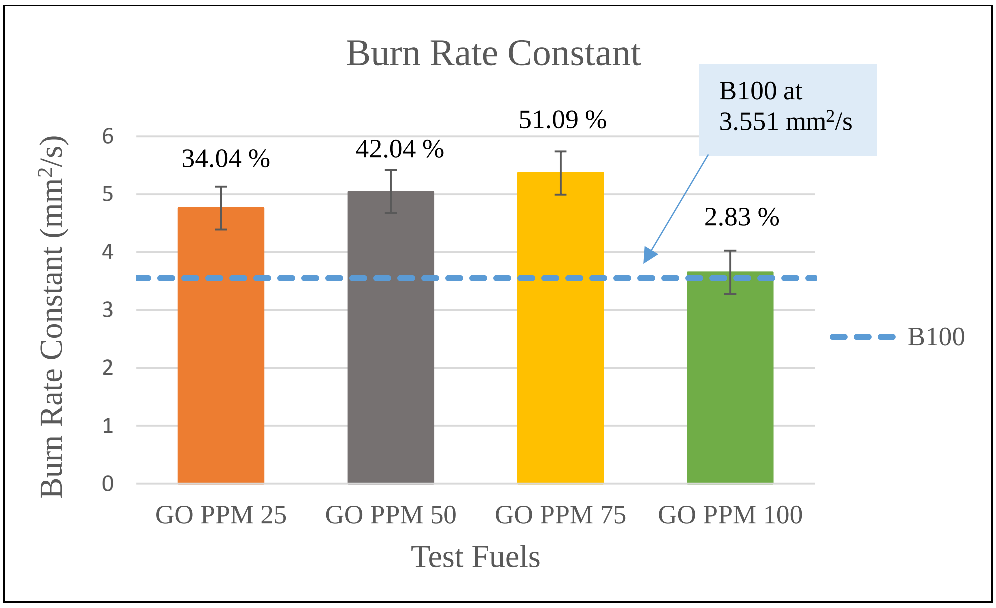


Figure 4.7: Burn Rate Constant of the Test Fuels.

The OH-functionalised nanoparticles is reported to enhance the burn rate due to the increase of reaction rate and heat transfer (Ghamari and Ratner, 2017). During the burning of Nano-fluid fuel, the burn rate constant was observed to be increased when the concentration of the nanoparticle fluid increases based on the experiment outcome from Tanvir and Qiao (2016). In the experiment, the burn rate constant increases as the concentration of GO increases in the B100. This trend does not apply for the GO PPM 100 Test Fuel.

It is observed that the highest concentration of GO among the test fuels which is GO PPM 100 has the smallest percentage increase in burn rate constant by 2.83 % at 3.6514 mm^2/s when compared to B100. The increase of the concentration of GO will increase the burn rate constant of the test fuel, but it is not applied in this case. As reported from Gan and Qiao (2011), adding more particles beyond the optimum concentration of the nanoparticles was observed to have a reduction in burn rate constant. This is due to the formation of large aggregation of the GO. This investigation shows that the concentration of GO is excessive in the blend of GO PPM 100 and caused the formation of bigger GO particles. This reduces the surface area of the GO particles to conduct heat transfer and hence lower combustion rate.

From the results in Figure 4.7, GO PPM 75 has the greatest burn rate constant at 5.3652 mm^2/s. It has 51.09% of increase in burn rate constant compared to the B100. This concluded that PPM 75 is the optimum concentration for GO to be blended in

B100 to achieve the desired burning behaviour. Therefore, the use of GO PPM 75 in the diesel will result in a more complete combustion that helps to improve the performance of the engine. Less heat will be conducted through the wall of engine cylinder and the brake thermal efficiency will be improved.

4.5 Combustion Duration

Combustion duration of the test fuel is the time taken for the test fuel to burnout from its auto-ignition state. The combustion duration of the test fuel can be affected by the burning behaviour that has been mentioned previously, which are the ignition delay and the burn rate constant. The times taken to complete the combustion of all the test fuels are shown in Figure 4.8. It can be observed that GO PPM 50 and B100 have the similar time taken for the fuel to burn out at 1.75 seconds, whereas the other has shorter combustion duration.

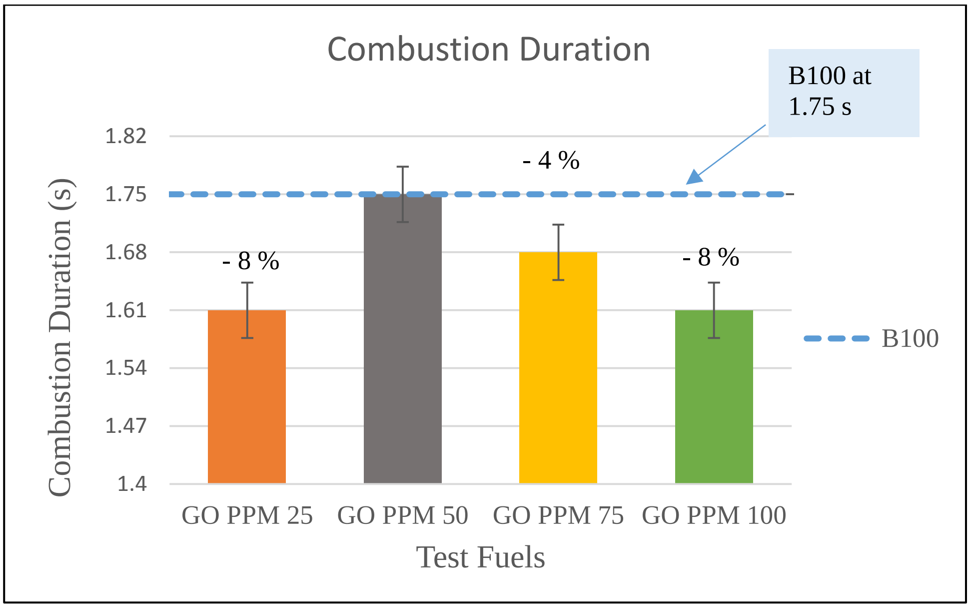


Figure 4.8: Combustion Duration of the Test Fuels.

By comparing the ignition delay of the test fuel with the combustion duration, it has the trend of shorter ignition delay will lead to the shorter combustion duration. This relation of the trend applies to all the test fuels in this investigation by comparing with Figure 4.5 that shows ignition delay.

From EL-Seesy, Hassan and Ookawara (2018), it was learned that lower flame speed provides a longer time for the NO_x to form. The NO_x can be reduced by reducing the combustion duration. This indicates that the combustion duration is related to the amount of NO_x emission. Based on Figure 4.5, B100 and GO PPM50 have the highest combustion duration among the test fuel and they will have the highest NO_x emission theoretically.

The additional of GO in the B100 will cause higher emission of NO_x when compared to B100 under the same condition. This investigation result is supported by the report from Hoseini et al. (2018). This phenomena also found in EL-Seesy, Hassan and Ookawar (2018) and it is concluded that the blend of B100 with GO shows an increase of mean temperature and NO_x emission. Therefore, it can be concluded in this experiment that the GO PPM 50 in this experiment will emit the highest amount of NO_x. However, GO PPM 25 and GO PPM 100 have the lowest emission at the combustion duration of 1.61 s.

GO PPM 25 has the lowest combustion duration due to higher occurrence of micro-explosion and bubbling during the end of the burning stage. This has been explained in Chapter 4.2. From Figure 4.1, it shows the plotted line of GO PPM 25 has the most obvious of fluctuation at the end of the burning stage that enhance the fuel consumption time. Bubbles are observed in the burning test fuel at the unsteady stage in Figure 4.2 and Figure 4.3. These phenomena helped the GO PPM 25 fuel to be more effective in burning out.

GO PPM 100 also has the shortest combustion duration similar to GO PPM 100 due to its high concentration of GO. The excessive of GO concentration has resulted the great decrease in burn rate constant, but it helps to shorten the burning duration. Large amount of GO solid particles aggregated at the centre of fuel droplet due to its high concentration in the droplet. Nanoparticles tend to move to the centre of the droplet as discussed in Chapter 4.2. This causes the droplet of GO PPM 100 to burn vigorously at a fast pace at the end of burning stage when sufficient of heat is received at the core of the droplet.

GO PPM 75 shows the average of combustion duration among the test fuels in this investigation at 1.68 s. It has a shorter combustion duration compared to B100 at the reduction percentage of 4% because micro-explosion occurs at the end of the burning stage too as observed from Figure 4.1. Other than that, it also has a good amount of GO concentration in its blend that helps to burnout faster at the end of the burning stage. This shows GO PPM 75 has the good characteristics of the GO PPM 25 and GO PPM 100 blends and maintaining a short combustion duration.

4.6 Problems that Affects the Results

From the report of EL-Seesy, Hassan and Ookawara (2018), the factors that will influence the ignition delay of a fuel are the air temperature, pressure, oxygen concentration and fuel properties. The reason of low accuracy in the results as can be observed from Figure 4.5, where B100 and GO PPM 50 test fuels have the same ignition delay. This can be due the air temperature during the investigation of burning. The air temperature and pressure around the burning droplet are not maintained throughout the whole experiment because the chamber is not fully sealed. There are holes needed to be at the side of the chamber to allow the accessibility of the glow plug and camera. Therefore, this traded off the sealing chamber. Furthermore, the moved out action of the glow plug when auto ignition had successfully occurred also change the air speed and surrounding air pressure.

Presence of larger aggregates of GO will cause higher frequent of micro-explosion phenomena (Ghamari and Ratner, 2017). The inconsistency of the size of GO in this experiment caused the inaccuracy data of the experiment, such as the occurrence of micro-explosions in the burning test fuels. To solve the issue, GO container should be stored in a clean room and avoid to be in moisture room environment that will cause the particles of GO to clump with each other easily. Therefore, the average data of each test fuels were used in analysing the burning behaviours to minimize the error of inconsistency.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A comprehensive study of combustion characteristics of B100, GO PPM 25, GO PPM 50, GO PPM 75 and GO PPM 100 was carried out using a single droplet experiment. A graph of normalised area against time was plotted for all the test fuels and three burning stages of the test fuels were identified. The burning stages are preheating stage, steady burning stage and unsteady burning stage. The GO blends have shown overall improvement in the combustion behaviours compared to the B100. All the test fuels have the trend of increasing in droplet size during preheating stage and have the trend of size decrement after ignition take place. GO PPM 25 and GO PPM 75 have shown to have the most obvious fluctuations during the increase and decrease of droplet size. This is due to the greater amount of occurrence of bubbling and micro-explosions phenomena.

GO PPM 100 has the shortest ignition delays at 2.8 seconds among the test fuels. The increase concentration of GO in the fuel blends will increase the amount of oxygen molecules and cetane number. They catalyse the combustion behaviour and promote a shorter ignition delay in the test fuels. This explains the decreasing trend of ignition delay across the higher concentration of GO in the test fuels. Less temperature in the combustion chamber is needed when the fuel has shorter ignition delay. Subsequently, lesser amount of NO_x will be emitted due to lower flame temperature. Nevertheless, increase of cetane number will reduce the emissions of CO, PM and UHCs.

GO PPM 75 has the highest burn rate constant at 5.3652 mm^2/s among the test fuels. The OH- functionalised nanoparticles and high thermal conductivity of GO helps to enhance the burn rate when its concentration increases. However, burn rate of the highest concentration of GO PPM 100 blend did not increase much compared to B100. This is believed that large aggregation of GO particles was formed when the concentration of GO is beyond the optimum limit. The fuel with high burn rate constant tends to have a combustion that is more complete and less heat will be conducted to the engine cylinder.

In this experiment, it is observed that the trend of combustion duration is inversely proportional to the trend of ignition delay. Longer ignition delay will lead to shorter combustion duration. Shorter combustion is favourable because it has lower emission of NO_x.

Based on the results, GO PPM 75 is found to have the best concentration of GO in the blends. This is because it has the highest burn rate constant and has enhanced by 51.09% compared to B100. Besides, it also has the higher frequency of micro-explosions compared to GO PPM 100 that contributes to the performance of combustion. GO PPM 75 also has the shorter ignition delay and combustion duration compared to B100 at the percentage reduction of 7.69% and 4% respectively. The amount of GO in GO PPM 75 blend has effectively enhanced the burning behaviour of B100 and reduced the pollutants emissions.

The results in this investigation have shown the potential of GO as the additive to improve the burning behaviour of B100. More efforts should be invested in Palm Biodiesel-Graphite Oxide blends because it could substitute the use of diesel and solve the environmental issue from the fuel emissions.

5.2 Recommendations for future work

For future works, the optimum heat for the fuel blends to ignite can be investigated. This is due to heating methods and heating temperature will be affecting the burning behaviour of the fuel too. Besides, the further research can focus on the ignition process of the multicomponent droplets. This is to study the other factors of affecting the ignition delay of the test fuel such as ambient temperature, pressure and radius of the droplet.

Another study that is worth to investigate is the finding best method to produce the best quality GO. A method that is low cost, simple and environmental friendly should be investigated. This is to convince the industry market to focus in the potential applications of GO to be mixed with the B100.

Lastly, future work should focus in solving the problem of sedimentation of GO in the B100. This will cause problems in the working engine whereby most of the particles are deposited at the bottom of the fuel tank. It is suggested to have a long-term investigation in order to understand the possibility of the adverse effect of GO operating in diesel engine.

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APPENDICES

APPENDIX A: Tables for Combustion Behaviours of all the Test Fuels.

Table A.1: The Ignition Delay of the Test Fuels.

Test Fuels	**Ignition Delay (s)**
B100	3.64
GO PPM 25	3.15
GO PPM 50	3.64
GO PPM 75	3.36
GO PPM 100	2.80

Table A.2: The Burn Rate Constant of the Test Fuels.

Test Fuels	**Burn Rate Constant (mm^2/s)**
B100	3.5510
GO PPM 25	4.7599
GO PPM 50	5.0437
GO PPM 75	5.3652
GO PPM 100	3.6514

Table A.3: The Combustion Duration of the Test Fuels.

Test Fuels	**Combustion Duration (s)**
B100	1.75
GO PPM 25	1.61
GO PPM 50	1.75
GO PPM 75	1.68
GO PPM 100	1.61