EFFECT OF ETHANOL ON THE COMBUSTION CHARACTERISTIC OF PALM BIODIESEL

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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 2020

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

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ABSTRACT

The use of diesel fuel has contributed to the environmental degradation due to its harmful emission. Particularly, the main pollutants emitted from the burning of diesel fuel include particulate matter (PM), carbon monoxide (CO), nitrogen oxide (NOx) and unburnt hydrocarbons (UHC). In addition, the increasing global demand for diesel fuel has caused the depletion crisis of the fossil fuels. Therefore, there is a need in searching of an alternative fuel for diesel engines. Biodiesel-ethanol blends may be a solution to the aforementioned issues. The present study aims to investigate the effect of ethanol on the combustion characteristics of palm biodiesel. In which palm biodiesel and its blend with ethanol at 10 %, 20 % and 30 % blending ratios are the fuels under investigation. Single droplet combustion experiment was adopted to study the combustion characteristics of the test fuels, through a time-based image capturing method. Thereafter, the images of the combustion process were then going through image processing using MATLAB to obtain the temporal variation of droplet area and diameter during combustion. Finally, classical D^2 law was used for the computation of burn rate constant for the test fuels. In regard to the experimental results, BE blends (palm biodiesel-ethanol blended fuel) have shown an adverse effect on the ignition delay. The prolonged ignition delay is likely attributed to the higher latent heat of vaporization and lower cetane number of the ethanol. Yet, BE blends have shown improved performance on the burning rate and combustion duration, with a maximum improvement of 23.15 % (increased burn rate constant) and 16.39 % (reduced combustion duration) respectively at 30 % ethanol composition, owing to their high oxygenated content that promotes a cleaner and more complete burning process. While these are not the only gains, it is found that the micro-explosion events occurred more intensively with increasing ethanol content, resulting to an enhanced evaporation rate of fuel and improved air-fuel mixing process.

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LIST OF SYMBOLS / ABBREVIATIONS

B	Spalding transfer number
c_p	specific heat capacity, J/(kg·K)
D	diameter, mm
h_c	heat of combustion, kJ/kg
h_{fg}	latent heat of vaporization, kJ/kg
K	burning rate constant, mm^2/s
k	thermal conductivity, W/m·K
P	pressure, bar
q	heat per unit mass, kJ/kg
r	radius, mm
t	time, s
T	temperature, K
Δ	difference
ρ	density, kg/m^3
υ	stoichiometric air to fuel ratio
B	biodiesel-in-diesel blend
BE	biodiesel-ethanol blend
BBu	biodiesel-nbutanol blend
fps	frames per second
ICE	internal combustion engine
CI	compression ignition
SI	spark ignition
PM	particulate matter
NOx	nitrogen oxide
CO	carbon monoxide
EGR	exhaust gas recirculation
DOC	diesel oxidation catalyst
DPF	diesel particulate filter system
DEF	diesel exhaust fluid
SCR	selective catalytic reduction system

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

An internal combustion engine (ICE) works by converting the chemical energy of fuel into mechanical energy, whereby the ignition as well as burning of the fuel occurs within the engine block itself. Combustion is defined as an exothermic chemical process that gives off heat energy through the reaction of fuel and the air mixture. To be specific, the fuel will react with the oxygen from the air and releases energy to the surrounding in the form of heat and light. The engine will then partially convert this energy derived from the combustion process into mechanical work.

In general, ICE can be classified into two types, namely: rotary engine and reciprocating engine. Rotary engines are mainly driven by a rotor within the engine to generate power. Whereas reciprocating engines utilizes the reciprocating motion of the piston within a cylinder to produce a rotary motion on the vehicle's wheel. In reality, reciprocating engines are broadly utilized in automobiles and they are further classified into two types, which are spark ignition (SI) and compression ignition (CI) engines (Duleep, 2004). Looking at the basic working principle of a reciprocating engine which comprises of a moving piston and a fixed cylinder, the combustion gases will expand and thus pushing the piston, resulting in a rotary motion of the crankshaft. Ultimately, this rotary motion drives the vehicle's wheels through a design of gears and powertrain system.

As the name implies, the difference in SI engines and CI engines falls on the process of supply and ignition the fuel. For instance, in a SI engine, the combustion of fuel is accomplished with the aid of the spark plug situated in the head of cylinder to produce spark for ignition. The fuel being used in this engine is gasoline or petrol, therefore spark ignition engines are also called gasoline or petrol engines. While in a CI engine, ignition of fuel is done by exerting high compression pressure to the fuel. Diesel is the fuel being utilized in this case; hence they are also known as diesel engines.

The world today has a huge reliance on petroleum-derived fuels such as diesel and petrol. In most applications, these liquid hydrocarbon fuels are mixed with the oxidising agent and burn in spray form of fine droplets through the processes known as spray combustion and atomization. Diesel engine is one of the most widely used applications for spray combustion, while other relevant systems include gas turbine engines, rocket engines and oil-fired furnaces (Khan, *et al*., 2007). Therefore, a thorough understanding of the working principles of spray combustion is important for developing these systems, for the purposes of increasing the combustion efficiency and reducing the emission of pollutants. However, spray combustion is a complex process which comprises various chemical and physical reactions that occur at the same instance. For a better understanding of spray combustion, detailed analysis is needed for every each of these complex reactions, such as heat and mass transfer, change of phase, multicomponent two-phase flows and so on. This can be achieved by investigating a single fuel droplet rather than the actual spray form, since the spray is a collective of fine individual fuel droplets in dispersed phase.

Recently, concerns have been expressed on the long-term availability of these non-renewable fuels and also the adverse effects associated with the combustion of these fuels which give rise to environmental deterioration. Hence, it is wise to produce replacement fuels as a precautious to the day when the non-renewable fuel is fully excavated. Researchers has been investigating the production of alternative fuels for the diesel engines and it is found that several potential fuels are capable of replacing the diesel such as biodiesel, butanol, producer gas, dimethyl ether and hydrogen (Kumar, *et al.*, 2018). However, not all of these fuels are capable to fulfil the combustion system performance requirements, availability of fuel, and the sustainable development to reduce negative impact on the environment. Thus, further investigations are required in search of the best replacement fuels that satisfy these conditions. One area that need to be focused on is the droplet combustion of multicomponent fuel, which is the mixture of two or more liquid fuels. This is because by mixing these liquid fuels, we can obtain the beneficial properties of each of the constituents to compensate the lack or shortcomings in its pure form and thus producing a useful alternative fuel.

Hence, the main motivation of the present work is to investigate on the combustion behaviour of biodiesel-ethanol fuel blends by conducting an experimental examination of the burning of fuel droplet through a time-based image capturing method.

1.2 Importance of the Study

According to Statista (2019), the daily demand for crude oil in 2019 amounted to 100.6 million barrels in a global scale. Figure 1.1 presents the daily demand of the world for crude oil over the past 13 years, which shows a clear increasing demand trajectory. With this increasing trend of global demand on the crude oil, soon it will become a realistic scenario for these finite resources to be completely depleted. Ultimately, this will potentially impact on the economy and society if our current logistical infrastructure has not responded in time due to the heavy dependence on the massive supply of crude oil. The current study may have impact on providing an alternative fuel to reduce the reliance on these non-renewable resources.

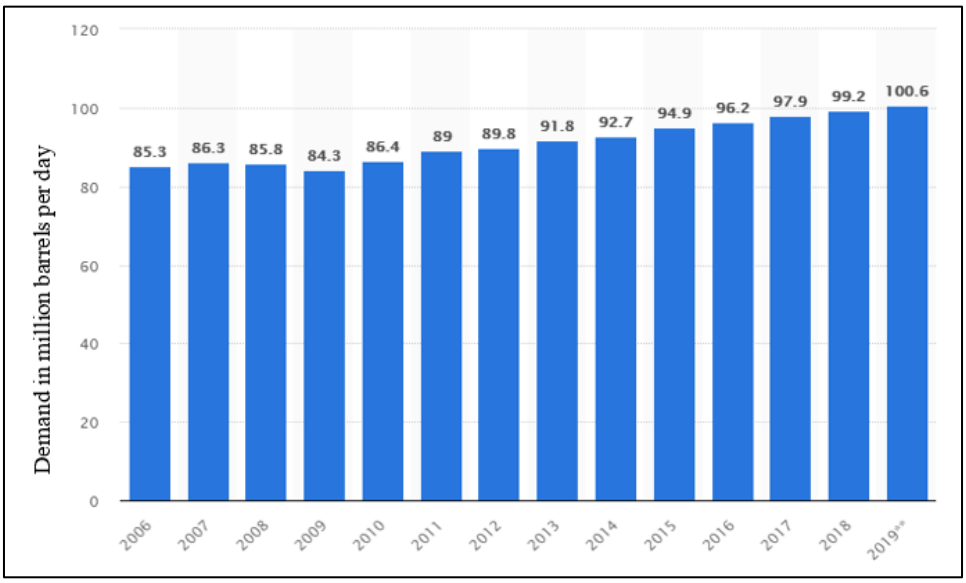

Figure 1.1: Daily global demand for crude oil from 2006 to 2019 (Statista, 2019).

Also, the emission of particulates from the motor vehicles is obviously one of the most significant sources of air pollution in many urban areas (Shuhaili, Ihsan and Faris, 2013). In fact, the actual process in an internal combustion

engine is usually incomplete combustion which cause it to become the major contributors to air pollution, especially CI engines that produce a great amount of soot. The main pollutants emitted from CI engines include particulate matter (PM), carbon monoxide (CO), nitrogen oxide (NOx) and unburnt hydrocarbons (UHC). The current study is essential to take the current understanding about the emission of pollutants from CI engines a step further in order to reduce its adverse effects to the environment.

To deal with these environmental issues, there were many investigations conducted to develop the alternative fuel. Several factors such as the composition and the associated combustion behaviour are important to determine the feasibility of it as an alternative fuel. It is necessary to have profound knowledge on the fuel properties and also the working mechanism of spray combustion so that improvements can be conducted on the engine design as well as the fuel composition.

In conclusion, the current study is essential to explore the combustion behaviour of the palm biodiesel-ethanol fuel blend. The experimental data may be used as reference to identify the optimal palm biodiesel-ethanol fuel blends concentrations that allow the combustion system to perform at its highest efficiency. On top of that, information from the study may be utilized to construct computer simulations for the processes in the combustion systems such as spray combustion and atomization.

1.3 Problem Statement

Problem statement for the current study on the combustion of palm biodiesel-ethanol fuel blends are summarized as follows:

Biodiesel is extensively recognised as comparable fuel to diesel in CI engines owing to several of its beneficial characteristics such as reduced emission of pollutants, higher cetane number, non-toxicity and so on. However, the poor low temperature flow characteristic of biodiesel is constraining its application in the CI engines (Misra and Murthy, 2011). Improvement on its cold flow characteristics still remains one of the key problems when utilizing biodiesel as a replacement fuel for CI engines. Although there are several studies suggest that addition of low viscous fuels such as alcohol-based fuels to biodiesel can improve its physical properties. Its detailed combustion

characteristics are yet to be explored and understood. Thus, further investigations need to be conducted and the current work aims to study the effect of ethanol on combustion characteristics of palm biodiesel.

Another question remains here is to come out with a feasible setup and strategy for the experiment since there are various techniques for droplet combustion investigation such as Schlieren imaging, self-illuminated direct imaging and backlighting imaging. The deciding factors fall on the budget available, complexity of the method and the conditions of working space. In addition, the assumptions made for data analysis remain one of the key variables in determining the accurateness of the results obtained. Thus, the assumptions to be used for the analysis must be appropriate and adequate.

1.4 Aim and Objectives

The main objective of the present work is to investigate the effect of ethanol on the combustion characteristic of palm biodiesel. More specifically, the aim of this study can be subdivided as follows:

- To design and build the experiment setup, particularly a combustion chamber to investigate the combustion of single fuel droplet.
- To investigate the droplet combustion characteristics of palm biodiesel-ethanol blends with different blending concentration of ethanol.
- To determine the optimum palm biodiesel-ethanol blending concentration that has better combustion characteristics than that of palm biodiesel.

1.5 Scope and Limitation of the Study

The scope of the current study includes heterogeneous combustion of liquid fuel in air. Looking deeper into its practical application in diesel engine, the scope of study converges into the working mechanism on the combustion system, which involves spray combustion and atomization. The simulation of the complex processes in spray combustion can be achieved through burning of fuel droplet. Thus, the scope is further narrowed into the droplet combustion of liquid fuel. Finally, the current study also covers the investigations of the combustion behaviours of the biodiesel-ethanol fuel blend with various blending ratios.

One limitation of the current work is on the data analysis of the result using classical D^2 law. Accordingly, the values obtained using the classical theory of droplet combustion are just approximations instead of precise result. Since the assumptions made for simplifying the solutions and thus developing the theory, have ignored some effects of the chemical and physical reactions that occur throughout the burning of fuel droplets. Next, the experiment is limited to ambient environment only in the self-designed combustion chamber. Due to the lack of budget, the custom-made combustion chamber cannot be advanced to conduct the experiment in microgravity and/or free-falling conditions.

1.6 Contribution of the Study

Biodiesel has been investigated intensively in both academia and industry due to its environmentally friendly properties and its potential in replacing the fossil fuels burned by diesel engines. However, biodiesel possesses certain properties that restricted its usage in the vehicles' engines, particularly its poor cold-flow characteristics and high viscosity that can downgrade the burning quality. According to Hashim (2017), the Japan Automobile Manufacturers Association (JAMA) allows only palm oil-derived biodiesel to be used in the vehicle, and limited to a blending ratio of B20 (80 % neat diesel + 20 % palm biodiesel) only. Thus, various investigations were conducted to enhance the fuel properties of biodiesel by introducing additives to biodiesel or blending biodiesel with other potential fuels. Yet, there is lack of real-world data to compare and elucidate the burning properties of these blends. Therefore, the present work aims to develop an optimum fuel blend concentration for palm biodiesel-ethanol fuel that results in the highest combustion efficiency.

The novelty of this work is to explore the potential of palm biodiesel-ethanol blend as automotive fuel for diesel engines applications. The present work focuses on the droplet combustion behaviours, which significantly affect the combustion, performance and emission characteristics of a CI engine. This work will provide a comprehensive understanding in both quantitative and qualitative into the combustion behaviours of palm biodiesel-ethanol blends. The outcome of this study would also provide technical insight of the potential of palm biodiesel-ethanol fuel blends that is useful for researchers and scientists

working in the area of fuel technology and automotive. Furthermore, this study would also contribute to the development of theoretical/ideal droplet model for simulation and predicting the evaporation and combustion processes occurring in diesel engines.

1.7 Outline of the Report

The final report can be divided into five chapters that is organized in a sequential manner to present the development of the present study, beginning from the general introduction of the present work and finishing with the conclusions and recommendations for future work. The outline of the report is summarized as follows:

Chapter 1 comprises of the general introduction, importance of study, problem statement, main objectives, scope and limitations and the contribution of the study.

Chapter 2 outlines the literature review of the present study. The literature review involves the operating principles of liquid fuel combustion and the combustion characteristics of fuel as well as the existing improvement strategies for diesel engines. Following, the theoretical review of classical D^2 law and the fuel blend approaches are reviewed as well. The experimental approaches are also discussed in the last section of literature review.

Chapter 3 contains the methodology which covers the preparation of the experimental setup and fuel blends, and the formulation of experimental strategy. The chapter also involves the methods to analyse the retrieved data.

Chapter 4 then presents the main findings of the present study. Interpretation of the fuel droplet combustion is divided into two phases, namely the preheating phase and the burning phase. The combustion behaviours such as micro-explosion and droplet puffing have been discussed as well. The results of the combustion characteristics are all presented graphically through charts, graphs and tables, along with discussions or descriptions of the results.

Chapter 5 concludes the main findings of the present study and proposes recommendations for the some of the aspects of the present work to be improved. The recommendations serve as a guidance for further research in the future work.

Finally, all of the references used for the present work and the appendices are listed at the end of the report.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Combustion process is a rapid exothermic reaction which produces substantial heat energy that dissipates through the ambient environment as flame (El-Mahallawy and Habik, 2002). It involves a series of processes that begin with mixing of fuel and oxidant, follow by ignition and propagation of flame, and end by the yield of different combustion by-products as an outcome of the oxidation of fuel. Flame is an important component of combustion for some reasons. For instance, it is the region where fuel and oxidant intersect and react as well as the zone with the highest temperature throughout the burning process. Thus, it has drawn increasing scientific interest.

The flame is a self-sustaining and extremely fast propagating reaction in a thin zone between the oxidizing agent and fuel. It can be categorised based on several factors such as flow condition and types of reactants. In general, the flames are mainly classified according to the combustible mixture formation and the type of flow. In the former classification, flames are divided into Premixed flames and Non-Premixed flames (also known as Diffusion flames). As the name suggests, premixed flames occur when fuel and oxidizer are well mixed at ambient condition before being delivered to the flame zone. On the other hand, the non-premixed flames happen when the fuel and oxidizer are initially not mixed and react rapidly as they mix by entering the combustion zone separately. In the latter classification, flames are classified based on the flow behaviour of the reactants, into Turbulent flames and Laminar flames when the flow is turbulent and laminar respectively. Table 2.1 shows the examples of types of flames and its corresponding applications. Diffusion flames are widely utilized in most practical applications because it is safer to avoid intimate contact of the fuel and oxidant. Besides that, turbulence is highly preferred in combustion as compared to laminar flow because of the resulting mixing enhancement by turbulence flow. Also, laminar flames are slow processes and not economic.

Table 2.1: Examples of types of flame and applications.

Flame Type	Laminar	Turbulent
Premixed	Bunsen Burner	SI Engine
Non-Premixed (Diffusion)	Candle Flame	CI Engine

Furthermore, combustion can also be classified based on the reactants' physical state, which categorised into homogeneous combustion and heterogeneous combustion. Homogeneous combustion describes the burning of fuel and oxidant that are present in the same physical phase, for example the Bunsen flame. While the heterogeneous combustion on the other hand defines the combustion from fuel and oxidant that are initially not in the same physical states, for example the burning of liquid fuel in air. In fact, burning of fuel in air is broadly used in most of the combustion applications, which indicates that heterogeneous combustion will essentially occur in the multiphase burning of these solid and liquid fuels. Therefore, heterogeneous combustion of liquid fuels in air is included in the scope of the present study. It is important to carry out further investigations on heterogeneous combustion to acquire in-depth information on the combustion characteristics and the reactions that occur throughout the process.

A route map of the development of droplet combustion research is outlined in the literature review. From which, the general review starts from the introduction to liquid fuel combustion in diesel engine, and later converged into the applications in combustion systems involving spray combustion and atomization. The discussion is further narrowed to the combustion characteristics of fuel which include ignition delay, burning rate, micro-explosion and bubble nucleation. The next section will be reviewing the current improvement strategies for diesel engine, followed by the droplet combustion of fuel which is theoretically to be very close and similar to the actual spray combustion process. Following, fuel additives and fuel blend approach are discussed. Whereby an emphasis is placed on the how the potential alternative fuels can help to deal with the two major current issues faced by the world: environmental deterioration and fossil fuel depletion crises. Finally, the comprehension has covered the experimental approaches used for droplet combustion experiment.

2.2 Liquid Fuel Combustion

According to Williams (1990), liquid fuels are combustible molecules that can be harnessed to produce mechanical energy through combustion. In reality, burning of liquid fuels has highly contributed to the massive energy requirements of the world, particularly in power generation and automotive sectors. This is because of their higher availability as compared to solid fuels, in addition to their greater flexibility in storing and transporting these fuels in contrast to fuels in gaseous form. Most liquid fuels that are widely utilized in the industry are derived from petroleum such as gasoline, diesel and kerosene. Still, there are other types of liquid fuels which are not produced from fossil fuel, such as hydrogen fuel, ethanol and biodiesel.

Liquid fuel combustion may form various patterns based on the property and amount of liquid as well as the type of combustion system. Figure 2.1 shows the influence of geometry on the combustion pattern of liquid fuel. Some of these combustions form pattern of accidental fires, involving Pool fire and Spill fire. In which pool fire usually takes place in liquid fuels of free surface with depth more than 10 mm, such as liquid fuels in open tanks. The depth of liquid in this case is the dominating factor to determine the continuity of combustion and burning rate. For instance, higher depth will cause lower burning rate due to the longer path of heat propagation to the bottom of liquid. While spill fire is regarded as a subset of pool fire that happens in the combustion of leaking liquid fuel in an open space (Zhang, *et al.*, 2014).

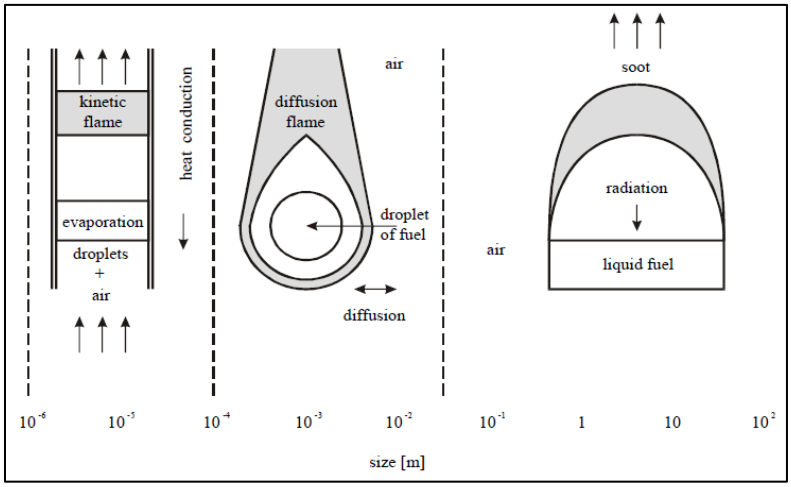

Figure 2.1: Influence of geometry on the combustion pattern of liquid fuel (Griffiths and Barnard, 1995).

In actual fact, combustion applications using liquid fuel are usually planned and controlled. Combustion of liquid fuel often takes place in the gaseous state since its evaporation point is normally lower compared to its ignition point. Therefore, the term volatility is used to describe the tendency of fuel to vaporize. Based on their volatility, liquid fuels are divided into non-volatile and volatile fuels. In the former, fuels are often evaporated during the burning of fuel, resulting in a diffusion flame configuration, as in the burning of diesel fuel in the CI engine. In the latter, fuels often evaporate first and mix with the oxidant, which subsequently burn in a premixed flame. Burning of petrol in the SI engine is an example to this type of fuel. In the case of combustion in the CI engine, injection of fuel in the spray form results in a highly pressurized and heated air, which causes the bulk of liquid fuel to disperse into fine fuel droplets and subsequently vaporize and burn locally. It is essential to have a profound knowledge of this individual droplet behaviour in order to elucidate the phenomenon of spray combustion, particularly to the nature and mechanism of the process. Hence, the scope of the present study involves liquid fuel spray combustion.

2.2.1 Spray Combustion of Liquid Fuel

Spray combustion system has many applications in the extensive field of combustion engineering, such as oil-fired furnaces, gas turbines, liquid rocket motors and diesel engines (Khan, *et al*., 2007). In this process, fuel is atomized into numerous tiny droplets to increase its total surface area for higher rate of evaporation that promotes the combustion process. A better understanding of the ignition process allows us to improve the performance of CI engines in terms of efficiency, safety and pollutant emission.

According to Warnatz, Maas and Dibble (2006), there are four main processes in liquid fuel combustion, which include formation of spray, evaporation of fuel, formation of combustible mixtures, and combustion of mixture. Initially, spray formation is the first step to form the fuel-oxidizer mixture in CI engine. The fuel spray is normally appeared after the fuel leaves the injection nozzle at high pressure (around 2000 bar). Upon leaving the nozzle hole, the liquid jet becomes entirely turbulent inside the hot combustion chamber very shortly from the discharge location. Figure 2.2 illustrates the

formation of spray by injecting fuel through the nozzle (Patterson, Donald and Henein, 1981). The injected fuel mixes with the surrounding air in the combustion chamber and raises the mass flow of the air toward x-direction due to the jet. At the same time, the jet spreads out in the y-direction resulting to the form of a conical spray. The jet velocity decreases gradually through the process due to the conservation of momentum as air is entrained into the jet as well as the frictional drag caused by fuel droplets. Referring to the velocity distribution at two cross sections as shown in Figure 2.2, it can be realized that the highest fuel velocity appears at the centreline and reduces gradually to zero at the interface between the spray form and ambient air.

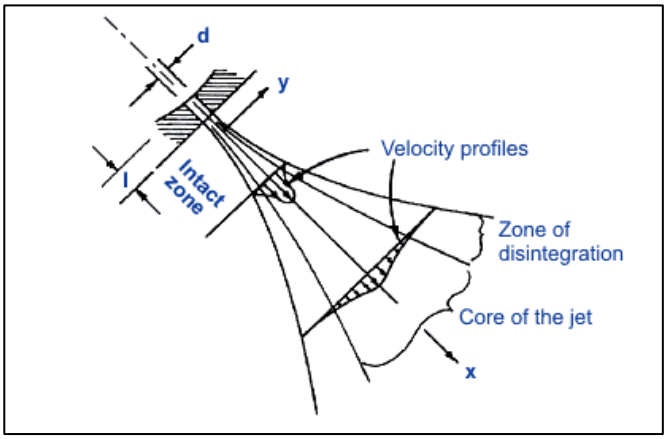

Figure 2.2: Formation of spray by injecting fuel through nozzle (Patterson, Donald and Henein, 1981).

Next, turbulence inside the liquid stream leads it to disperse into liquid threads that eventually develop into a thick cloud of variable size droplets which vaporize and mix with the oxidant in the combustion zone to initiate combustion. The process of breaking up of the liquid fuel to form droplets is called atomization. Atomization is an essential part of liquid fuel combustion. In fact, majority of the practical combustion systems such as industrial furnaces and internal combustion engines, operate on liquid fuel that must be atomized prior to combustion. Atomization helps in improving the combustion efficiency of such systems because of the increased fuel's surface area to mass ratio, which leads to a rapid evaporation and a more evenly mixing with the oxidizer, and therefore improves the mechanisms of heat and mass transfer.

2.2.2 Atomization

Atomization is the process whereby a liquid in its bulk form is dispersed into droplets by external and internal forces as an outcome of the interaction between the liquid fuel and the ambient medium. The disintegration takes place when the disruptive forces surpass the surface tension forces of the liquid fuel. The consolidating effect due to liquid surface tension tends to maintain the liquid in a form that gives off the minimum surface energy, whereas the stabilizing effect due to liquid viscosity tends to oppose any variation in liquid geometry.

The droplet formation by dispersion of liquid sheet was idealized by Fraser, *et al.* (1962) as shown in Figure 2.3. Due to the surrounding aerodynamic disturbances, the liquid sheet becomes increasingly unstable after discharging from the nozzle and spread out with a reduction in thickness to form the shapes of threads or ligaments. The further disintegration of the ligaments results in the formation of different size droplets. The initial break-up process is usually referred to as primary break-up, in which the larger droplets or ligaments produced in the initial disintegration process are still unstable and undergo further break up into smaller ones. This subsequent break-up process is often termed secondary break-up. In atomization, the liquid properties in both of the primary disintegration and secondary disintegration are the dominating factors to determine the resulting droplet size distribution.

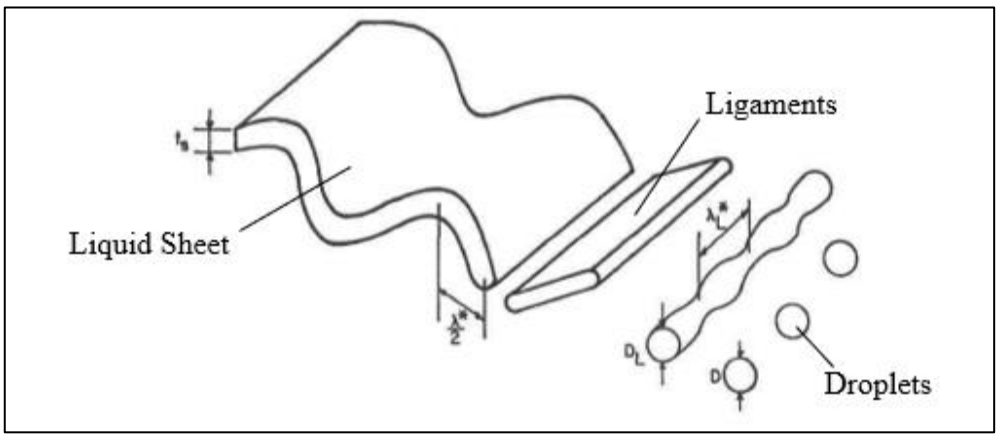

Figure 2.3: The liquid sheet disintegration. (Fraser, *et al.*, 1962)

The droplet size distribution can affect the engine performance, particularly in the process of spray combustion. According to Lee, Park and

Kwon (2005), it is realized that the increase in droplet size will increase the spray tip penetration distance and velocity, as the result of the lower evaporation rate owing to the enlarged droplet surface area. On top of that, droplet size will affect the flame structure as well. For instance, tiny droplets normally burn in a premixed gas flame because these droplets are fully vaporized upstream of the flame front, whereas a diffusion flame is observed in the combustion of large droplets. In addition, the injection of liquid fuels and the resulting spray atomization as well as droplet formation have a direct impact on the emission characteristics of the combustion process. Figure 2.4 shows the overall process of a spray combustion, from the injection of fuel until the completion of burning to emit the end products of fuel-oxidation. Based on studies of Sarv, Nizami and Cernansky (1983), it is found that the emission of NOx reduces with the reduction in droplet size in the spray as a result of enhanced rate of evaporation as well as the domination of premixed combustion mode. To sum up, droplet characteristics play an important role in defining the spray combustion and thus impacting the engine performance. Hence, the scope of the present study is further narrowed to the combustion of droplet.

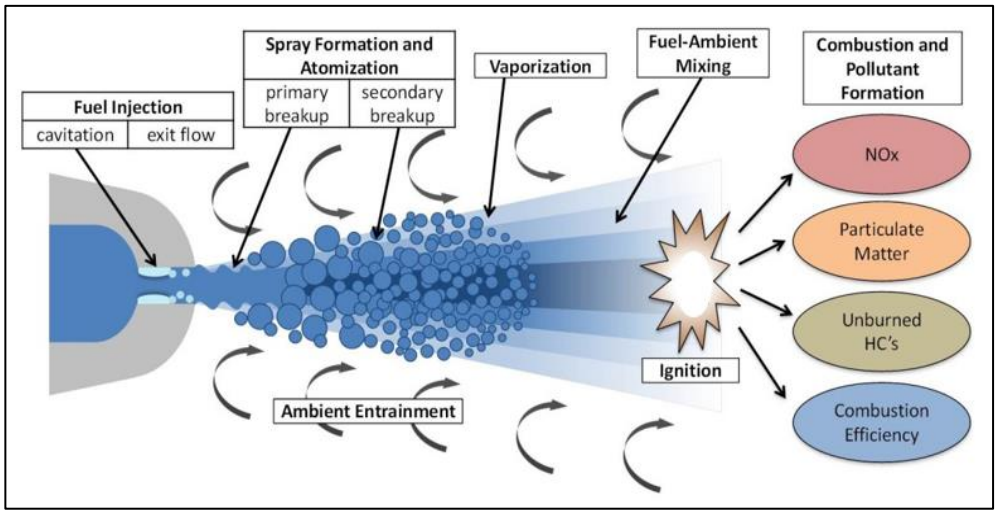

Figure 2.4: Overall spray combustion process (CFD and Propulsion Group, 2018).

2.3 Combustion Characteristics of Fuel

The present study involves investigation of the combustion characteristics of fuel. Therefore, a comprehensive review is conducted the combustion

characteristics such as ignition delay, burn rate constant, micro-explosion and bubble nucleation. Many researchers have used the aforementioned parameters to discuss their experimental findings. Thus, the factors affecting these parameters are reviewed as well.

2.3.1 Ignition Delay

Ignition delay is an important combustion characteristic that can cause an effect on the performance and emissions of a CI engine. In CI engines, ignition delay can be defined as the time interval starting from the injection initiation to the begin of ignition. In terms of engine performance, a shorter ignition delay period indicates even more diffusion burning occurs than the premixed burning throughout the combustion process, producing lower noise or engine knock. While in terms of exhaust emissions, a shorter ignition delay produces lower NOx emission but greater soot emission (Yap, *et al.*, 2019).

From Heywood (1988), ignition delay period is directly manipulated by both chemical and physical processes that occur prior to the burning of liquid fuel. For instance, the physical processes include spray atomization of liquid fuel, vaporization of liquid fuel droplet as well as mixing of vapor fuel with the air. While the chemical processes include the reactions of fuel with air and residual mixture of gases that lead to auto-ignition. Fuel properties, engine design and the operating variables are the main factors that are affecting these processes.

In regard to the factors affecting the physical processes, a good atomization needs high fuel injection pressure and optimally viscous fuel. Whereas the vaporization rate is affected by the droplets' size, distribution and velocity, which is controlled by the atomization process. Besides that, the in-cylinder pressure and temperature, and the volatility of fuel can affect the vaporization rate as well. Moreover, the mixing rate of fuel and air is manipulated by the design of combustion chamber and injector. For example, the shape of piston head can be modified to a spheroid cavity to generate a swirling motion to the air in the cylinder during compression stroke. The generated swirl motion can enhance the mixing rate of the fuel and air.

In regard to the fuel properties, Heywood (1988) reported that ignition delay period is highly depending on the cetane number of fuels, where low

cetane fuel will cause longer ignition delay, in which ignition may take place sufficiently late in the power stroke, leading to incomplete burning of fuel that deliver low output power and poor fuel economy. Contrary wise, short period of ignition delay can be achieved with high cetane fuel and resulting to a smoother engine operation. Ignition takes place before all of these fuels is being injected into the cylinder, and therefore ensures a more complete burning of fuel.

2.3.2 Burning Rate

The burning rate of the fuel indicates how fast the fuel is being consumed during combustion. For instance, increasing burning rate means shorter burning period of the fuel. Usually, high burning rate is desired in the diesel engines as it helps to minimize the heat loss from the combustion process. When the burning period is short, heat produced from the fuel can hardly escape from the cylinder wall, thus maintaining a high combustion efficiency (Ooi, et al., 2017). One of the factors that commonly deal with the burning rate is the oxygen content in the fuel. High oxygen content in the fuel favours a more complete combustion process, which indicates a cleaner emission with reduced NOx and CO. Another factor affecting the burn rate is the vaporization rate of the fuel. The vaporization rate is reflected by the fuel's boiling point. From which, a low boiling point means higher vaporization rate, and thus the fuel can be used up in a shorter period of burning time (Ooi, et al., 2017). Furthermore, the process of atomization during the fuel injection is directly related to the fuel's vaporization rate, where an enhanced atomization process with smaller fuel droplets can expose larger droplet's surface area to mass ratio, resulting to a rapid vaporization process, and subsequently improving the burning rate.

The burning rate of fuel can be defined by the burn rate constant, where the burn rate constant is originated from the classical D^2 law. This theory is created with several assumptions and it is reviewed in later section. Other possible combustion behaviours that may affect the burn rate constant is the micro-explosion events, which will partially or entirely break down the fuel droplet into even smaller droplets. The details of micro-explosion are reviewed in the following sub section.

2.3.3 Micro-explosion/ Puffing of Droplet

According to Shinjo, *et al*. (2014), micro-explosion in multicomponent fuel droplet can be described as the rapid breaking down of the fuel droplet triggered by the bubble formation and superheated boiling effect due to the lower boiling point component. While a less intensive breaking down of fuel droplet is usually termed as droplet puffing. In short, droplet puffing can be known as partial breaking down of the droplet parts instead of the whole fuel droplet. The breakdown of droplet part is achieved through the vapor jet produced from the droplet surface, where the vapor jet is regularly contained with tiny sub-droplets in scattered phase. For case of vigorous puffing, the continuous phase of fuel droplet may split up part of its content from the droplet exterior into even smaller droplets. The subsequent process of splitting up of the droplets can be known as secondary atomization. Droplet micro-explosion, puffing and secondary atomization are the processes of creating even smaller fuel droplets, thus these processes help to enhance the rate of vaporization of fuel and fuel-air mixing. These effects can improve the combustion efficiency of a CI engine. Micro-explosion occurrence is directly related to the nucleation and bubble formation in a multicomponent fuel droplet. A clear presentation of the progression of puffing and multiple puffing of droplet is shown in Figure 2.5. The physics of these combustion behaviours are within the scope of the present study as these behaviours directly affect the engine's combustion efficiency. The events are investigated through the magnified experimental visualization to track and observe the dynamics of fuel droplet from liquid to vapor phase.

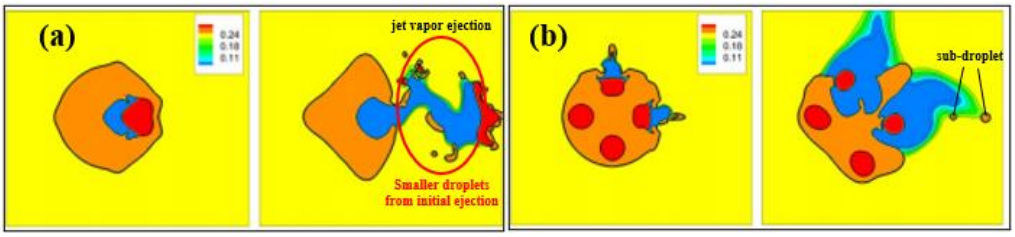

Figure 2.5: Dynamics of (a) puffing and (b) multiple-puffing of water-in-oil emulsion droplet (Shinjo, *et al.*, 2014).

2.3.4 Nucleation and Bubbles Formation

Generally, nucleation can be defined as a self-organizing process of a thermodynamic system that results to the formation of a new phase. For example, it is illustrated in the growth of crystal from crystal solution and the bubble generations in boiling liquid (Helmenstine, 2018). A crucial parameter to be known in this study is the nucleation limit in boiling, which determine the critical temperature where the liquid maintains its phase without undergoing phase switching. Occasionally, the energy yielded from the evaporating liquid at the critical point (nucleation limit) is adequate to trigger micro-explosion within the fuel droplet. The explosion happens mainly because of the extreme rate of bubble growth which exceeds the liquid response (Avedisian, 1985). Therefore, for burning of multicomponent fuel droplet, heating of the inner core of the droplet is carried out simultaneously through radiation and convection from external flames and surrounding hot gases. Owing to the distinct boiling points of the various components present in the multicomponent fuel, the component with lower boiling point becomes superheated at first and generates bubbles within the droplet once the droplet temperature has reached the nucleation limit. Because of the variation in densities, the bubbles tend to head towards the surface of the droplet as presented in Figure 2.6. It then ruptures at the droplet exterior due to the difference in pressure across the bubbles.

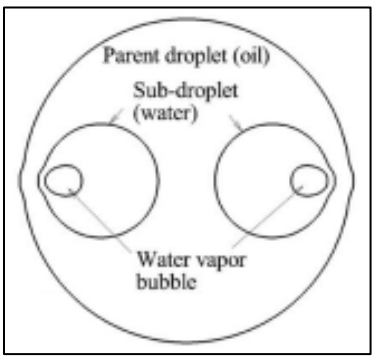

Figure 2.6: Schematic illustration of the formation of bubbles in water-in-oil emulsion droplet (Shinjo, *et al.,* 2014).

It is important to consider bubble nucleation that occurs in the multicomponent fuel droplet as it can enhance the vaporization rate of the fuel droplet and the mixing rate of the fuel and air. The present study involves the

investigation of the bubble generation over the combustion of fuel droplet, as the formation of the bubbles is directly affecting the combustion efficiency.

2.4 Current Improvement Strategies for Diesel Engine

This section includes some of the renowned methods that are used for improving performance and emissions in diesel engine such as exhaust gas recirculation, exhaust after-treatment system and diesel common rail direct injection.

2.4.1 Exhaust Gas Recirculation

Based on the paper authored by Jaaskelainen and Khair (2019), exhaust gas recirculation (EGR) is a method to regulate NOx emissions from diesel engines. Emissions of NOx can be lowered through EGR by heat absorption and reducing the oxygen content in the cylinder. As its name implies, EGR is conducted by returning part of the engine's exhaust gas to the cylinders. As a result, the exhaust gases have diluted the oxygen concentration from the intake air stream. Also, the exhaust gases function as heat absorbents to lower the peak in-cylinder combustion temperature as they are inert to the burning process. This effectively reduces the formation of NOx because the high temperature favours the production of NOx from the atmospheric nitrogen and oxygen in the combustion chamber.

2.4.2 Exhaust After-treatment System

Due to increasing attentions being raised on the harmful diesel emissions, most diesel-powered trucks have implemented exhaust after-treatment systems to filter and process the engine's exhausts before releasing the gases to the surrounding environment. Since the combustion by-products are treated after exiting the engine, these systems will not affect the output power and performance of engine.

Rueden (2017) states that the main components of the exhaust after-treatment system basically involve the selective catalytic reduction system (SCR) and diesel particulate filter system (DPF) as shown in Figure 2.7, which are functioned to lower the formation of NOx and particulates. Exhaust gases first pass through the DPF system, where the system is capable of filtering approximately 90 % of particulates from the exhaust gases by using diesel

oxidation catalyst (DOC) that helps to capture soot and oxidize CO. Before proceeding to the SCR system, the outputs from the DPF system have to go through diesel exhaust fluid (DEF) dosing to further lower down the NOx emissions, where the main composition in DEF is deionized water and urea. The process is accomplished by a pump and doser to deliver and inject DEF into the exhaust system. Thereafter, the mixing of decomposed DEF and the exhaust stream take place in the decomposition chamber before entering to the SCR. Inside the SCR system contains the catalyst to speed up the reaction of the decomposed DEF and exhaust stream, in order to meet the enforced limitation for the emission of NOx in diesel-powered vehicles.

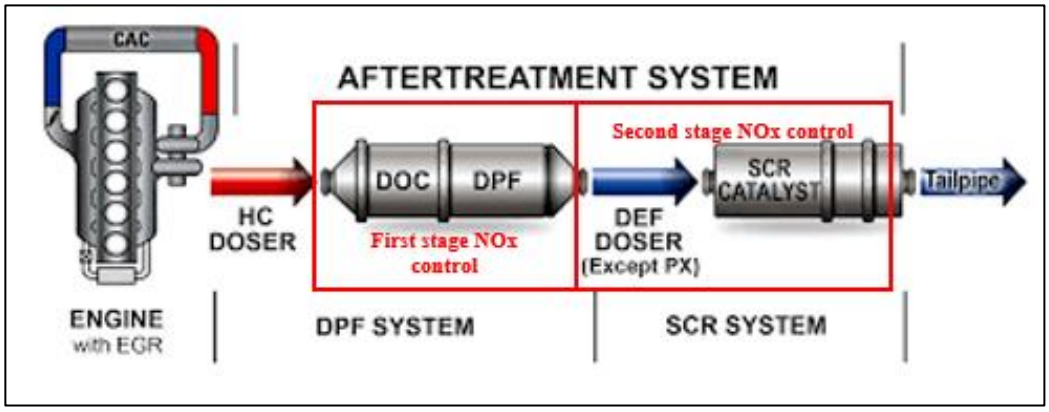

Figure 2.7: Diesel engine aftertreatment system. (Paccar, 2013)

2.4.3 Common Rail Direct Fuel Injection

According to Farinia Group (2020), modern diesel engines nowadays are implemented with common rail fuel injection system, which is a fuel injection technology that injects the diesel fuel directly into the combustion chamber. The major difference of this direct injection system compared to the conventional indirect injection system falls on the way how fuel is being delivered as well as the way the fuel mixes with the intake air. As mentioned earlier, direct injection system injects the fuel directly into the combustion chamber, which has skipped the idle time in the intake manifold. Also, the system is precisely manipulated by the electronic unit to inject the fuel at the hottest place in the combustion chamber, which results into an even and thorough burning process. Owing to the improved mechanism of heat and mass transfer, the common rail direct fuel

injection can enhance the engine performance in terms of reduced exhaust emissions, improved fuel economy and increased power output.

The system features a high-pressure pump, an electronic control unit, a rail and injectors. In short, the common rail describes a lengthy metallic cylinder which distributes the fuel collected from the pump to the injectors under very high pressure (up to 2000 bar). Spraying the fuel at high pressure allows better atomization of the fuel droplet by reducing the mean droplet size diameter. Also, the smaller droplet size increases the fuel's surface area to mass ratio, which causes a rapid evaporation and a more thoroughly mixing of fuel and air. The enhanced vaporization rate of fuel and the domination of premixed combustion mode consequently increase the combustion efficiency of the engine.

2.5 Droplet Combustion

Generally, there are mainly two types of research methods for spray combustion. The first method is depending on interpretation of the actual burning process through combustion of an idealized spray or individual fuel droplet. Whereas the second method involves direct observations of spray combustion by experimentally investigating the various associated effects and parameters such as radiation, stability, flame oscillation and flame length. In addition, theoretical investigation on spray combustion can be done using the information from turbulent gas diffusion combustion of individual fuel droplet (Onuma, Ogasawara and Inoue, 1977). It is essential to study droplet combustion due to its importance as an elemental process in spray combustion systems, as the spray atomizes into numerous tiny droplets with variable sizes prior to combustion.

There are usually two forms of droplet combustion, which are monopropellant droplet combustion and bipropellant droplet combustion. The first type describes the combustion of fuel (monopropellants) without the need of a separate oxidizer. Examples of monopropellants include hydrazine and its derivatives (Ambekar, *et al.*, 2014). While the second type involves combustion of fuel droplet with the aid of oxidizing agent, and it is more widely utilized in many industrial applications as compared to the first one.

2.5.1 Classical D^2-Law

Godsave (1953) and Spalding (1953) had conducted and designed the first ever simplest model to describe droplet evaporation and combustion, which is also called the classical theory of droplet combustion: D^2-law. Primarily, the classical theory offers a fundamental foundation in order to develop more applied and empirical descriptions of spray combustion. It provides an elementary speculation on surface regression rate and illustrates the basic physics of fuel droplet. Figure 2.8 shows the model demonstrating the burning of an individual liquid fuel droplet in a stagnant oxidizing medium. In this geometry configuration, the fuel droplet vaporizes at its surface to form vapour and diffuses outward, meanwhile the oxidizer diffuses inward from the surrounding environment. Stoichiometric reactions take places between the fuel and oxidizer, leading to the formation of a non-premixed flame zone. Finally, the heat produced is dissipated from the flame by radiation and conduction to the droplet surface and ambient environment. Table 2.2 shows the assumptions made in the development of the classical D^2 law.

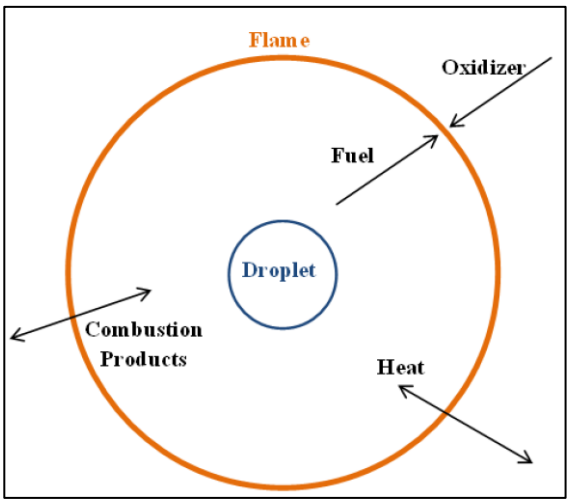

Figure 2.8: Schematic diagram of Classical D2-Law combustion model (Law, 1982).

Table 2.2: Assumptions made in the classical theory of droplet combustion (Godsave, 1953).

I.	Gas phase quasi-steadiness.
II.	Chemical reaction infinitely fast with respect to diffusion.
III.	Isobaric process.

IV.	Spherical symmetry.
V.	Isolated droplet in infinite medium.
VI.	Constant gas phase transport properties and heat capacity.
VII.	Constant droplet temperature.
VIII.	Ignores Soret effect, Dufour effect and radiation.
IX.	Radiation is negligible.
X.	Buoyancy is negligible.
XI.	Unity Lewis number for all gaseous species.

Based on the assumptions stated in Table 2.2, the classical D^2-law deduces that the flame stand-off position, droplet burning rate and flame temperature remain unchanged throughout the droplet burning lifetime, and are described by the equations as follows:

The droplet burning rate constant is defined as:

$$K = \frac{8k_g}{\rho_l c_{pg}} \ln[1 + B] \tag{2.1}$$

whereby

K = droplet burning rate constant, mm^2/s

k_g = gas thermal conductivity, W/ m·K

ρ_l = liquid density, kg/m^3

c_{pg} = specific heat of gas, kJ/kg·K

B = Spading transfer number

Flame stand-off ratio is evaluated in terms of the droplet radius as shown:

$$\frac{r_f}{r_s} = \frac{\ln [1+B]}{\ln [\frac{1+\upsilon}{\upsilon}]} \tag{2.2}$$

where

r_f = flame radius, mm

r_s = droplet radius, mm

υ = stoichiometric air to fuel ratio

Temperature of flame is evaluated in terms of stoichiometric fuel/air mixture, fuel properties and droplet surface temperature as:

$$T_f = T_s + \frac{q_i + h_{fg}}{c_{pg}(1+v)}[vB - 1] \tag{2.3}$$

where

T_f = flame temperature, K

T_s = droplet surface temperature, K

q_i = heat per unit mass, kJ/kg

As mentioned above, *B* denotes the Spalding transfer number, which is a non-dimensional thermodynamic parameter, and it is expressed as:

$$B = \frac{(\Delta h_c / v) c_{pg} (T_\infty - T_s)}{q_i + h_{fg}} \tag{2.4}$$

where

Δh_c = difference in heat of combustion, kJ/kg

T_∞ = ambient temperature, K

h_{fg} = latent heat of evaporation, kJ/kg

Generally, the time-based droplet size variation equation, which is also called the classical D^2 law is shown as:

$$D^2(t) = {D_0}^2 - Kt \tag{2.5}$$

where *D* is the diameter of droplet at time *t* and D_o is the initial diameter just before ignition. Thereby, the lifetime of burning droplet can be obtained by substituting $D^2(t_d) = 0$;

$$t_d = \frac{{D_0}^2}{K} \tag{2.6}$$

The D^2-law is well established for the combustion of liquid fuel droplets. It states that throughout the burning process of the droplet, the square of the

instantaneous droplet diameter varies linearly with the elapsed time (Sakai and Saito, 1983). Nevertheless, all of these predictions using classical D^2-law represent only the approximate values since the assumptions made for development of the theory, have neglected the some of the effects occur in the actual droplet combustion process. For example, the assumption of gas-phase quasi-steadiness helps to simplify the conservation equations by removing the time-based variable, but at the same instance it ignores the transient processes which involves ignition and heating of fuel droplet. Accordingly, since the values obtained using the classical D^2 law are just approximations, they are mainly applied for estimation purposes instead of precise computations. Still, the parameters established by the D^2 law has become the crucial characteristics to be evaluated in most of the research investigations carried out for droplet combustion

2.6 Additives

Additives are usually introduced to the fuel to form a multicomponent fuel for certain purposes, particularly to achieve desired fuel properties that work optimally for certain applications. Multicomponent fuel or mixtures of fuels can exist in three different forms, which are: blends (for example diesel blending with alcohol), slurries (as in the mixtures of coal and water) or emulsions (such as oil and water emulsions). Majority of fuels in the market are used in the form of multicomponent fuels rather than in its pure form for some reasons. Primarily, they are used to improve the performance of the combustion system in terms of the combustion efficiency, by introducing fuels with higher heating value. Next, they are used to minimize the emission of pollutants from conventional fuels, which are harmful to the environment. The third reason is due to the crises of fuel resources depletion, particularly to the fossil fuel resource that the world has a massive reliance on, in our everyday lives. Owing to the aforementioned reasons, numerous experiments have been conducted to add various components to the conventional fuels in search of the best alternative fuel that is able to fulfil the performance requirements of combustion system and support sustainable development. Ultimately, it is found that biofuels and alcohols are widely used with the conventional fuels in many combustion systems, due to their exceptional properties to minimize the emission of pollutants such as soot and

NOx, as well as the fairly similar combustion efficiency as compared to those conventional liquid fuels.

Chemical reaction will not take place between the constituents in the mixtures of fuel, and each constituent maintains its own unique chemical and physical characteristics. Hence, combustion of multicomponent fuel droplet is significantly more complex than the fuel droplet in its pure form, since various components are being burned simultaneously in the mixture (Wang, Liu and Law, 1984). Accordingly, various constituents of the fuel mixture possess different evaporation rates and different boiling points, resulting to a concentration gradient in liquid phase within the droplet. Also, it is expected to have a variation in volatility tendency because of the different boiling points of each constituent. This indicates that the higher volatile constituent will vaporize first until their concentrations are decreased, and thus altering the concentration gradient within the droplet. The change of concentration gradient has promoted an internal circulation inside the droplet, since the higher volatile constituent tend to diffuse outward the surface to evaporate, and the lower volatile constituent will tend to diffuse inward, resulting to relative motion within the droplet. The difference of concentration on the droplet surface along its lifetime has an impact on the evaporation rate (Sirignano, 2010). Thus, the dominating factors that have an effect on the burning process of multicomponent fuel droplet are: (i) the miscibility of the constituents, (ii) the relative concentration and volatility of each constituent, and (iii) the relative motion within the droplet. The present study aims to investigate the droplet combustion characteristics of palm biodiesel-ethanol blends at different blending concentrations.

2.6.1 Biodiesel

According to Han, *et al.* (2017), nowadays the clean replacement fuels for internal combustion engines have been received increased consideration due to the crises of fuel resources depletion and environmental degradation. Among numerous alternative fuels, biodiesel is a promising alternative fuel due to its similar chemical and physical properties to those of fossil diesels. The exceptional characteristics of bio-diesel that make it a potential alternative fuel are the low sulphur content, and higher flash point, lubricity and cetane number. Also, it is environmentally friendly with the properties of biodegradable,

oxygenated and non-toxic. Owing to the alikeness in composition with the fossil diesel, biodiesel can be directly used in the traditional CI engines without significant modification. The effect of biodiesel fuels on engine emissions is that biodiesel is shown to be potentially capable to reduce the emission of pollutants including carbon monoxide, unburned hydrocarbons, and particulate matter.

Their shortcomings on the other hand include the properties of high viscosity and pour point, and the low calorific value and volatility. In addition to their low oxidation stability and hygroscopic nature, which have made them easily to corrode different engine parts. Due to these disadvantages, it is usually recognized that with only up to 20 % bio-diesels blend with diesel, can be utilized in the CI engines without modifications (Sathiyagnanam and Saravanan, 2011). Studies from Jiang, *et al.* (2019) present that the poor atomization property of biodiesel is due to its relatively high viscosity and surface tension. Furthermore, owing to the high pour point, its flow problems become obvious at low temperatures. The main disadvantages of biodiesel fuels are associated with the highly increased viscosity, which is usually ten to twenty times higher than the conventional diesel fuel. Even though experiments using biodiesel displayed promising engine performance, but this result remains for short term only since problems appeared after the engine had been operated for extended periods.

Looking deeper into the type of biodiesel, palm biodiesel is a potential candidate of sustainable fuel to be utilized in CI engines. In contrast to biodiesel derived from oil of plants, palm biodiesel is economically beneficial by its energy yield and it is less expensive (Yap, *et al.*, 2019). Table 2.3 illustrates the comparison of fuel properties of biodiesel (B100), its blends with 50 % addition to diesel fuel (B50) and diesel fuel. Based on Table 2.3, it is found that the biodiesel's viscosity is tremendously (122.5 %) higher as compared to diesel fuel. In terms of density, biodiesel is about 5.88 % greater than diesel fuel. On top of that, in terms of heating value (calorific value), biodiesel is about 7.56 % lower than diesel fuel. This indicates that greater amount of biodiesel fuel is required to be applied to the combustion system to generate the same amount of power as conventional diesel fuel. Generally, fuels are considered safe with flash point exceeded 52 ℃. Therefore, biodiesel is very safe to be handled since

its flash point has surpass this safety threshold and it is even greater when compared to flash point of diesel fuel.

Table 2.3: Comparison of fuel properties of B100, B50 and conventional diesel (Sathiyagnanam and Saravanan, 2011).

Properties	B100	B50	Conventional Diesel
Density @ 15 ℃ in gm/cc	0.8835	0.8610	0.8344
Specific gravity @ 15 ℃	0.8848	0.8610	0.8360
Kinematic viscosity @ 40 ℃ (mm^2/s)	6.83	4.12	3.07
Flash point (℃)	150	108	60
Calorific value (kJ/kg)	40789	43124	44125
Cetane number	52	52	51

2.6.2 Alcohol

According to Jiang, *et al.* (2019), there exists a solution to the aforementioned problems and disadvantages of biodiesel, which is introducing the low viscous fuels with reduced surface tension into the biodiesel. By doing so, the low viscous fuel is capable to enhance the degraded spray characteristics and thus improve the fuel-oxidizer mixing process. Alcohol is one good example of these low viscous fuels to enhance the combustion process. For instance, the oxygen present in the alcohol gives rise to a more complete burning process and thus improving the thermal efficiency of the engine. Several studies have proposed ethanol and butanol as the potential additive fuels.

Firstly, ethanol possesses good cold-flow characteristics and low viscosity, in addition to their highly oxygenated content. These are beneficial properties for biodiesel which help to enhance its fuel properties in terms of better cold-flow characteristics, reduced viscosity and increased volatility. Also, the increased oxygen content of ethanol helps to promote a cleaner burning process that can further lower down the emission of PM. Experiments had been carried by Bhale, Despande and Thombre (2009) to investigate the fuel properties of

ethanol blended with biodiesel. It was found that the reduction of cloud point from 18 ℃ to 8 ℃ can be attained with addition of 20 % concentration of ethanol in Mahua biodiesel. While in terms of engine emissions, the findings of Bhale, Despande and Thombre (2009) revealed that a reduced NOx, CO and smoke exhausts are found in the biodiesel-ethanol blended fuel when compared to the pure biodiesel.

Besides that, butanol is another potential alcohol-based additive fuel with greater calorific value, lower latent heat of vaporization and higher cetane number as compare to that of ethanol. Experimental findings of Lapuerta, *et al.* (2018) for investigating the fuel properties of biodiesel blended with butanol revealed that the pour point and cloud point decrease with the increasing butanol concentration in the biodiesel-butanol blends. Another investigation was carried out by Vinod, Madhu and Amba (2017) further discovered that addition of butanol enhances the fuel properties of biodiesel. As a consequent, the combustion process was promoted leading to lower level of soot and CO produced and higher brake thermal efficiency, but with a penalty in increased fuel consumption.

2.6.3 Palm Biodiesel-Ethanol Fuel Blend

Experiments had been conducted by Yoon, *et al.* (2009) to investigate the spray characteristics of biodiesel-ethanol fuel blend through spray visualization and analysing size of droplet. The outcomes of the experiments show that the BE10 (10% ethanol addition to biodiesel), BE20 and diesel fuel have similar spray penetrations, yet diesel fuel has larger average particle size as compared to those of BE10 and BE20. Another experiment regarding the comparison of combustion behaviour and emission of biodiesel-ethanol (BE) and biodiesel-nbutanol (BBu) blends had been conducted by Wei, Cheung and Ning (2018). It is found that BE blends are better in minimizing the emission of NOx and pollutants in a direct-inject diesel engine, but these blends also possess adverse effects on the performance of engine, particularly at low load. In fact, it is shown that the BE blends are worse than the BBu blends in terms of the adverse effects introduced to the engine performance. Accordingly, further investigations of droplet combustion of the biodiesel fuel with ethanol addition are important for a better understanding of the combustion characteristics such as flame

appearance and burning rate, which helps in improving low temperature flow property of the biodiesel fuel and atomization enhancement.

2.7 Experimental Approaches

The experiment for droplet combustion can be conducted in three conditions, namely the normal gravity condition, the microgravity condition and the free-falling condition. The very first microgravity-conditioned droplet combustion was carried out by Kumagai and Isoda (1957) with the objective to verify the spherical symmetry assumption made in the D^2 law by neglecting the buoyancy effect as well as the heat convection on the burning rate of droplet. Figure 2.9(b) shows that the buoyancy effect causes the visible flame to form an oval shape instead of in the shape of spherical as assumed by the D^2 law. Without the gravitational disturbance, an almost perfect spherical droplet can be maintained throughout the burning period as illustrated in Figure 2.9(a). The setup of this method requires a minimal-gravity environment. This study is appropriate in investigating the burning behaviour of the fuel for outer space application such as spacecraft engines, where the safety issues of the use of fuel in microgravity condition is considered (Hu et al., 2012).

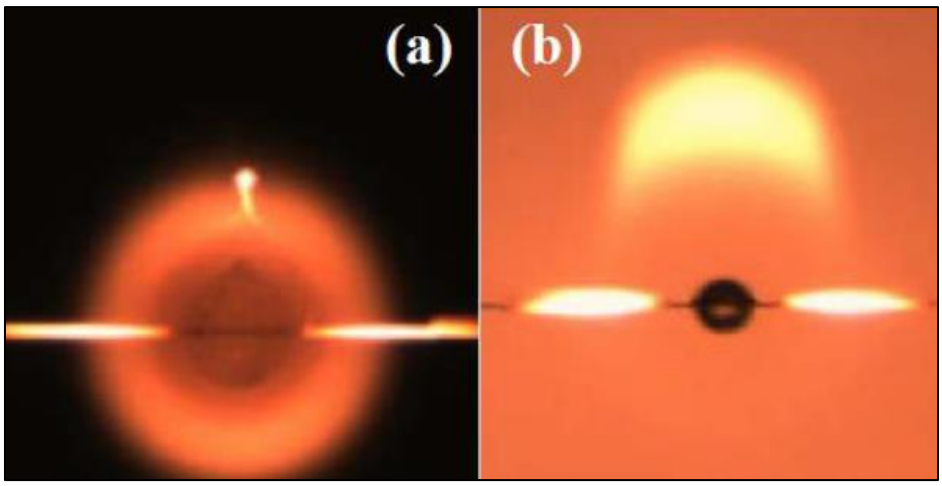

Figure 2.9: Shape of droplet's flame for (a) microgravity condition and (b) normal gravity condition (Pan, *et al*., 2009).

Another droplet combustion technique is to conduct the experiment in free-falling condition, where fuel droplets are let to "free fall" in a post-combustion region, which can be a flat-flame burner or a space of hot furnace

(Wang, Liu and Law, 1984). This allows the droplet to self-ignite when it is in the combustion zone. In this case, the combustion environment as well as the droplet's condition can be manipulated. For instance, the droplet's size and velocity and the combustion temperature can be controlled.

Finally, the normal gravity condition is the simplest and most economic method to conduct the droplet combustion. Most researchers have carried out single droplet combustion under normal gravity condition using the suspended droplet method, where the fuel droplet is suspended on a droplet suspender (usually made of silicon carbide fibre, steel wire, or even on the thermocouple wire). Assumptions for the classical D^2 law as mentioned previously in Table 2.2 have to be incorporated into the interpretation this single droplet combustion experiment such as quasi-steady state condition and spherical symmetry throughout the combustion (Williams, 1990).

2.8 Summary

The literature review has covered the beneficial properties of biodiesel that enable it to be an alternative fuel for neat diesel in diesel engines. Somehow, biodiesel also possesses certain properties which limited its usage in the diesel engine. In which, the flaws of biodiesel fall on its poor cold-flow performance and high viscosity. Owing to these disadvantages, several studies have proposed various methods for enhancing the fuel properties of biodiesel. From which, introducing additive fuels is a wise method as the desired fuel properties can be attained by introducing the right additives to the base fuel and mixing them at the right proportion. Studies have shown that alcohols are potential additives to biodiesel as they are low viscous and highly oxygenated. These beneficial characteristics from alcohols may help to get rid of the aforementioned disadvantages of biodiesel. Ethanol has been proposed to be a potential additive to biodiesel as it owns the beneficial characteristics as mentioned earlier, in addition to its good cold-flow performance. Investigations have been conducted on BE blends to study its spray penetration performance and exhaust emissions. The results for both studies have shown a promising advantages of ethanol addition to the biodiesel, with enhanced atomization and reduced PM and NOx emissions. Yet, there is lack of investigation regarding the single droplet combustion of BE blends. Thus, the present work is devoted to the droplet

combustion behaviours of BE fuel blends. The experiment findings of this study will provide technical insight of the potential of palm biodiesel-ethanol fuel blends that is useful for researchers and scientists working in the area of fuel technology, and even for the engineers working in automotive field.

Furthermore, single droplet combustion experiment is adopted in the present work as this experimental setup is fairly simple and not expensive. In addition, single droplet combustion is theoretically to be very close and similar to the actual spray combustion process. Therefore, the practical combustion parameters can be effectively investigated through this experiment. In the experiment, biodiesel will take up the significant volume in the BE blends since it is the main subject under investigation. In contrary, ethanol additives are just to find out how much improvement can be attained in the combustion characteristics as compared to the benchmark fuel: palm biodiesel. Therefore, the range of blending ratio covers only a small portion of ethanol, with only up to 30 % ethanol addition. Hence, the present work is dedicated to develop an optimum BE fuel blend concentration that can produce the highest combustion efficiency, within the stated blending ratio range.

Accordingly, the following chapters are dedicated to the experimental work and result. Detailed explanations of the experimental setup and strategy as well as the work plan are to be presented in Chapter 3, in addition to the image processing methods to analyse and compute the combustion parameters of palm biodiesel-ethanol fuel blends.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The current experimental work aims to investigate the effects of addition of ethanol to the combustion characteristics of palm biodiesel droplet. This experiment is conducted with time-based image capturing as the main method for observing the droplet physics throughout its burning lifetime. The measures and procedures to be taken in consideration throughout the experimental work are outlined as follows.

This chapter is dedicated for depicting the experimental processes. First and foremost, equipment and materials used are outlined in section (3.2), followed by the discussion of experimental setup in section (3.3). Next, the fuel preparation of palm biodiesel-ethanol fuel blend is demonstrated in section (3.4). Whereas the experimental procedure is outlined in section (3.5). Finally, data analysis which involves the algorithms used for image processing using MATLAB software are presented in section (3.6).

3.2 Equipment and Material

The preparation phase for the practical work of the present study can be divided into two parts, which are the design and construction of the experimental setup, and the preparation of the test fuels. For the equipment and materials used for the pre-experimental work, plywood, 0.5 mm steel wire, 12 V glow plug, white translucent paper, alligator clips and wires, 40 W standard halogen light bulb, and 12 V calcium battery were used to construction the experimental setup. For fuel preparation of the other hand, the equipment and materials needed include test tubes, measuring cylinder, ultrasonic cleaner, micro-fine syringe and hypodermic needle as well as the fuels which are biodiesel and ethanol. While during the experiment, Iphone 7 camera (120 fps, 1080p HD) and a tripod stand were used to retrieved the data.

3.3 Experimental Setup

Figure 3.1 shows the schematic diagram of the setup of experiment apparatus for droplet combustion test, while Figure 3.2 shows the completed prototype of the experimental setup. The self-design combustion chamber is partially enclosed with two opening spaces for the insertion of glow plug and the camera. There is another opening for the backlight illumination but it is closed off with a piece of white translucent paper, which serves as light diffuser for the purpose of reducing the light intensity of the backlight sources. In this case, a 40 W halogen light bulb is utilized as the backlight to retrieve a shadowgraph image of the droplet combustion. Steel wires are arranged in cross-link manner and serve as droplet suspender to hold the fuel droplet which is about 2 mm in diameter. The droplet is ignited by using a movable glow plug, in which the tip of glow plug is positioned about 3 mm beneath the fuel droplet. A movable glow plug is designed so that it can be removed from the fuel droplet once the droplet is ignited to avoid the glow plug from disturbing the view during the recording. Finally, a handphone camera (Iphone 7 model) is used to capture the combustion event at a resolution of 1080p HD (1920 x 1080 px).

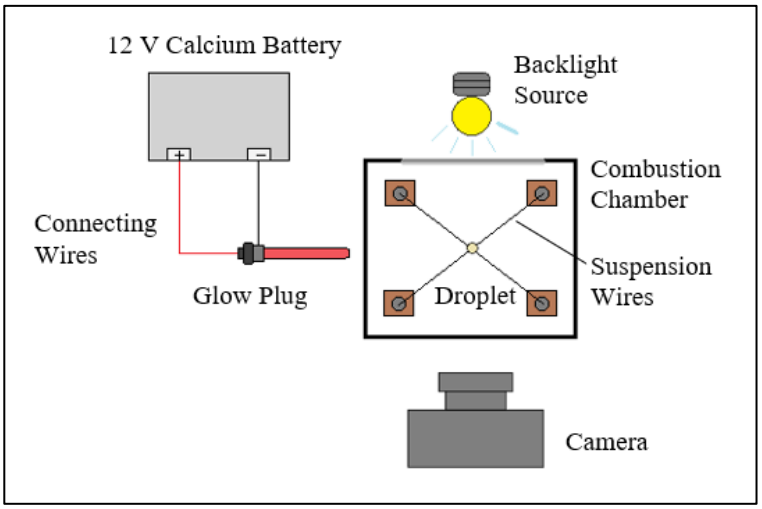

Figure 3.1: The schematic diagram of the setup of apparatus (Top view).

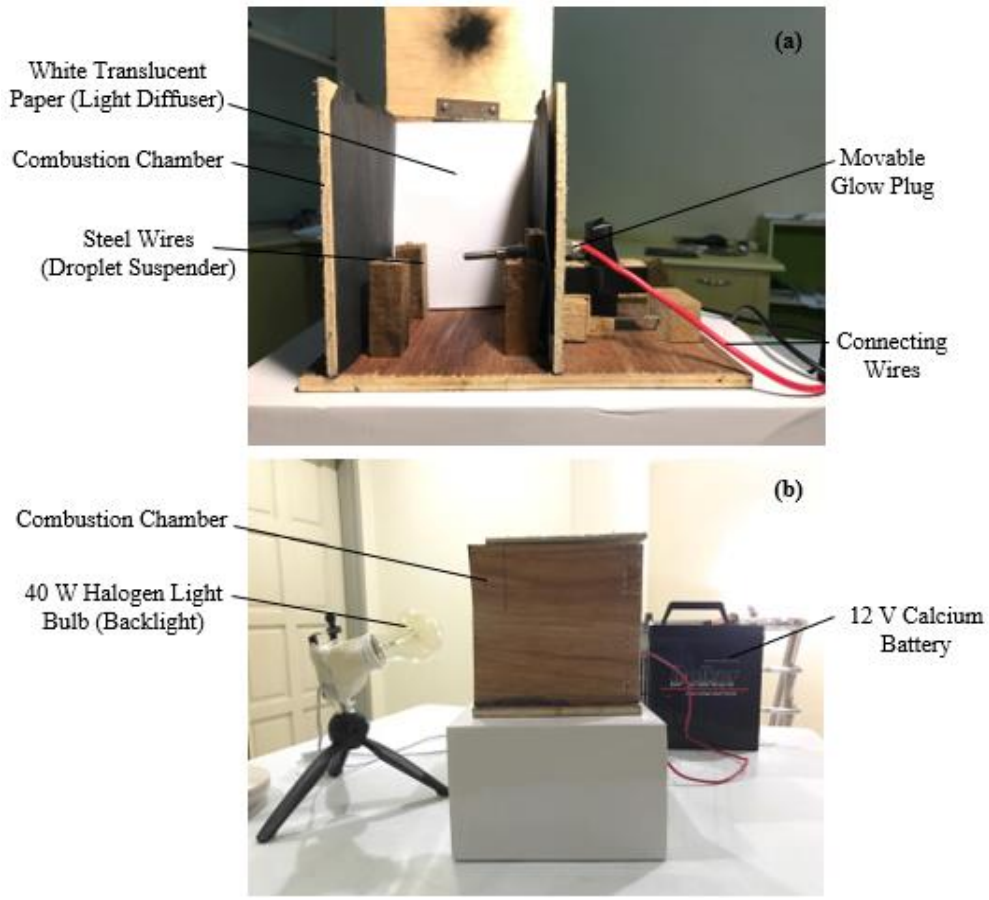

Figure 3.2: The completed prototype: (a) Front view, and (b) Side view.

3.4 Fuel Preparation

Fuel blending is the addition of additives, liquid fuel, and/or other substances to the base fuel by mixing them at various concentrations to yield a fuel blend of specific performance properties. The experiment is intended to investigate the combustion behaviour of different palm biodiesel-ethanol fuel blend compositions. Particularly, biodiesel (B100), BE10 (90 % biodiesel + 10 % ethanol), BE20 and BE30 are the test fuels for this experiment as presented in the Table 3.1. These blends are mixed based on volume to volume ratio. Take the preparation of BE20 as example, if a 50 ml of the blend's total volume is desired, this indicates that palm biodiesel in the blend comprises of 80 % of the total volume which is 40 ml, the remaining 10 ml is contributed by the ethanol. The specifications of the palm biodiesel and ethanol retrieved from supplier are presented in Table 3.2 and 3.3 respectively, where the biodiesel-ethanol blends used in the present work are created from palm methyl ester derived-biodiesel and pure ethanol with a purity of 99 %.

Table 3.1: Blending concentration of test fuels.

Test fuels	Blending concentration by volume percentage	
	Palm Biodiesel	Ethanol
B100 (Benchmark fuel)	100 %	-
BE10	90 %	10 %
BE20	80 %	20 %
BE30	70 %	30 %

Table 3.2: Palm biodiesel fuel specifications (ExcelVite, 2015).

Properties	Palm Biodiesel
Density (g/ml@15 ℃)	0.860−0.900
Viscosity (mm^2/s@40 ℃)	3.5−5.0
Flash point (℃)	315−350
Cetane number	51

Table 3.3: Ethanol fuel specifications (Elite Advanced Material, 2015).

Properties	Palm Biodiesel
Density (g/ml@20 ℃)	0.791
Viscosity (cP@25 ℃)	1.2
Boiling point (℃)	78.0
Flash point (℃)	14.0
Autoignition temperature (℃)	363.0

Due to the low miscibility of ethanol in palm biodiesel, it is difficult to ensure that they are well-blended. The test fuels must be well-mixed prior to the experiment, which require the use of ultrasonic cleaner. The ultrasonic cleaner will emulsify the blend in sonicated bath by producing cavitation bubbles through high frequency pressure waves to create a vigorous agitation to the fuel blend. The agitation process forced the molecules of the constituents to adhere to each another, resulting to a well-blended homogenous fuel after a sufficient agitation time. Finally, the fuel preparation is completed and the test fuels are ready to be stored in the syringe.

3.5 Experimental Procedure

Since the experimental setup is self-designed and custom-made, it does not require any special standards or measures to its operation throughout the experiment. The experiment procedures are summarized as follows.

The first step is the droplet generation by using a micro-fine syringe with needle to transfer a fine drop of palm biodiesel onto the droplet suspender. Once the fuel droplet is set ready, the cover of the combustion chamber is closed for the purpose of making the combustion system enclosed so as to avoid surrounding factors that can affect the experimental results. The glow plug is then activated by connecting it to the 12 V calcium battery. Once the glow plug is heated, the tip of the glow plug is oved and positioned beneath the fuel droplet. Meanwhile the video is started to record the combustion process. The glow plug is immediately removed from the fuel droplet once the fuel droplet is ignited. The combustion of the fuel droplet is observed and the video recording is terminated once the combustion process is ended. The glow plug is disconnected from the battery and wait for approximately 5 minutes for the temperature of glow plug to cool down before starting a new test. When idling, the wire is cleaned using towel paper to remove the residual unburnt fuel. This is to ensure the accuracy of data by preventing the contamination of the test fuel when starting a new test. Finally, the steps are repeated for various concentrations of palm biodiesel-ethanol fuel blends (I.e.: BE10, BE20 and BE30). A flowchart of the procedure of experiment is shown in Figure 3.3.

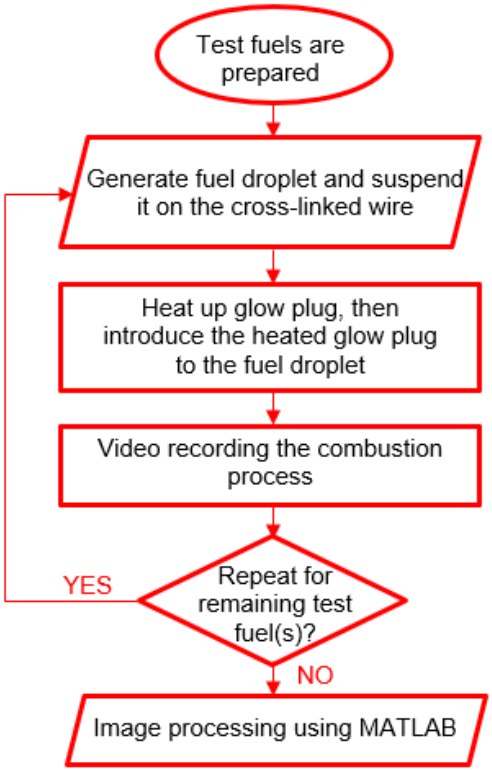

Figure 3.3: Experimental procedure flowchart.

3.6 Data Analysis

The combustion of fuel droplet is video recorded in monochrome and colour modes. These images are later extracted out and converted into binary images to investigate and observe the changes of droplet size throughout its burning lifetime. Since the camera being utilised has a frame rate of 120 fps, the changes in droplet size are able to be observed clearly. Next, the extracted images are processed using MATLAB software to calculate the number of pixels exists inside the droplet boundary. Finally, based on the number of pixels, the droplet diameter is computed.

3.6.1 MATLAB Binary Image Processing

After the desired images of different timeline throughout the combustion process are acquired, MATLAB software is used to convert these RGB format images to grayscale images, and then into binary images. These conversion processes to get a resulting image that is more appropriate for particular applications are known as image enhancement. In this case, the conversion of binary image is essential to facilitate the calculation of number of pixels

contained within the droplet for the computation of droplet area to investigate the burning rate. As its name implies, the pixels of binary image consist only two value, which are 0 and 1, which represent black colour and white colour respectively. Figure 3.4 shows the step by step image enhancement, segmentation and morphological operations. It clearly shows that the processed binary image makes it even easier to compute the number of pixels, at the same time it does not affect the original shape as well as the size. Also, image segmentation and some morphological operations are conducted to fill holes and divide the image into multiple parts as shown in Figure 3.4(d-f), so that the single fuel droplet can be clearly identified and other functions can be used to extract meaningful information from the image. In the current work, the area of the fuel droplet is extracted, by counting the number of pixels in the white zone.

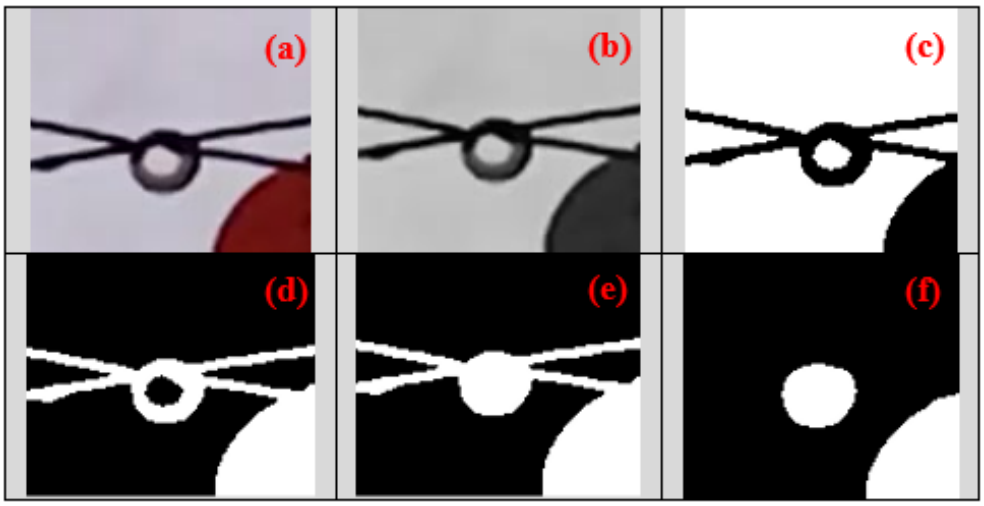

Figure 3.4: Imaging processing steps; (a) original image, (b) grayscale image, (c) thresholding, (d) complementation, (e) holes filling, (f) final image.

After the final image is obtained, data validation is performed mathematically and visually to make sure that the effects of image processing functions in terms on shape, colour and size are minimal in the resulting processed images, so that there is no discrepancy between the original image and the final one. Figure 3.5 shows the comparison of droplet's raw RGB format image and its corresponding processed image. The fuel droplet as shown in Figure 3.5 is extracted at the very beginning of the combustion process when the heat is introduced to the droplet, which is at the time interval 0 s. It is found

that the shape of the droplet distorted as it is not perfectly round, this is due to the adhesive action of the fuel to the cross-linked steel wire suspender, which has stretched it longer at the latitudinal side. Through mathematical analysis, the figure shows that the highest discrepancy found in both of the longitudinal diameter and latitudinal diameter is 1 pixel.

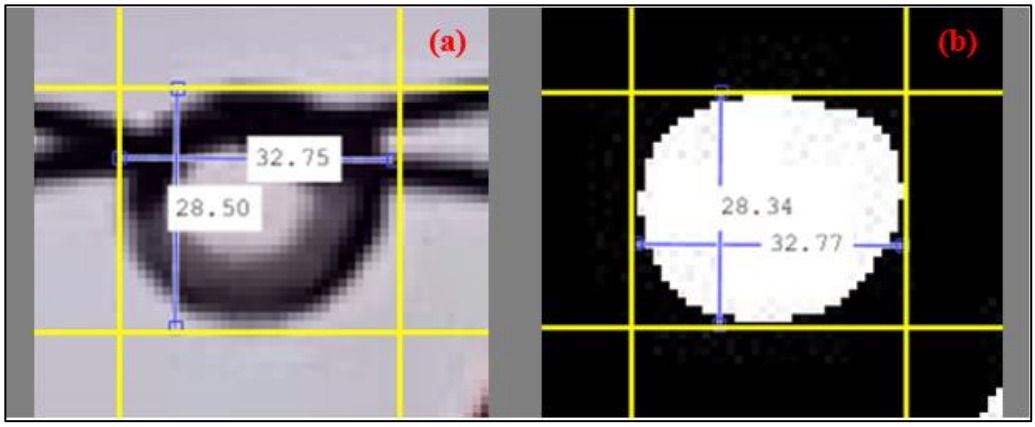

Figure 3.5: Mathematical analysis on (a) original image, and the (b) processed image.

For an example of visual inspection, it can be observed that the shape and size are similar for both original image and the processed image as presented in Figure 3.6. These data validation steps of mathematical analysis and visual inspection are done for many other cases of droplets at different time interval. It is to ensure that the discrepancy between the processed image and the original image is minimal, and to guarantee a more accurate and reliable data, before proceeding to the next step, which is computation of droplet burn rate.

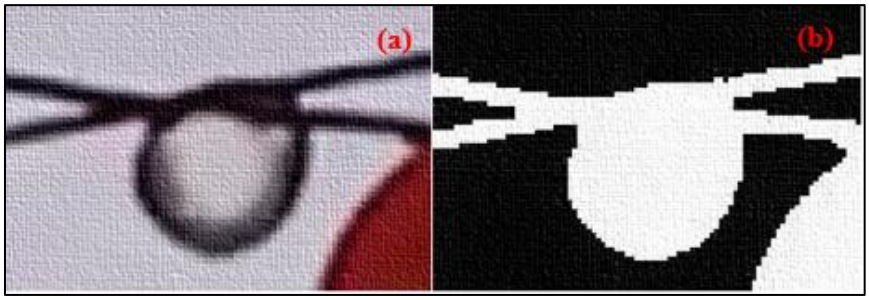

Figure 3.6: Visual inspection on the size and shape of the (a) original image and the (b) processed image.

3.6.2 Computation of Droplet Burning Rate

Another important parameter to be investigated is the burning rate of droplet. This can be achieved by using the equation derived from classical D^2 law, which was discussed previously in Chapter Two. Based on equation (2.6):

$$t_d = \frac{{D_0}^2}{K}$$

The burning rate of droplet is ratio of square of the initial diameter to the droplet burning lifetime. The burning lifetime is the interval starting from the ignition of droplet until the flame extinguished. Thus, the burning rate can be computed with the droplet area retrieved using the image processing method, and the droplet lifetime determined through the video recording. The initial diameter of the droplet can be easily calculated from the droplet area using equation for area of a circle as shown:

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

where

D = diameter of the fuel droplet, pixel(s)

A = area of the fuel droplet, pixel(s)

As mentioned previously, the area extracted within the boundary of fuel droplet is in the unit of pixel(s), and the diameter evaluated from the area based on equation (3.1) is in unit pixel(s) as well, therefore it needs to be converted to a viable unit to be applied in equation (2.6). Figure 3.7 presents the backlighting picture taken for the steel wire droplet suspender and the its corresponding shadowgraph image. As the actual diameter of the wire is known, the actual size of the droplet can be identified based on the wire size using the equation (3.2) as follows:

$$X_R = 0.5 \times \frac{X_{im}}{X_F} \tag{3.2}$$

where

0.5 is the actual diameter of the steel wire in unit mm

X_R = actual size of the object, mm

X_{im} = corresponding value of the object in the image, pixel(s)

X_F = size of the steel wire in the image, pixel(s)

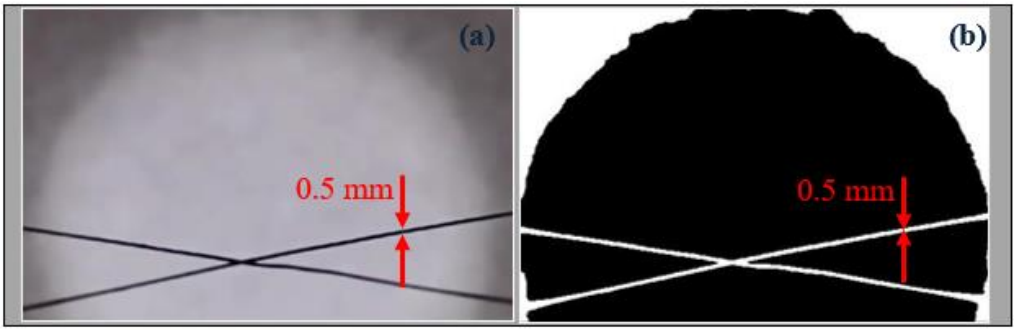

Figure 3.7: (a) Backlighting picture taken for steel wire droplet suspender and its (b) corresponding shadowgraph image.

To sum up, a flow chart of the data analysis for the present work is shown in Figure 3.8, which consists of the steps for imaging processing and computation of droplet burning rate.

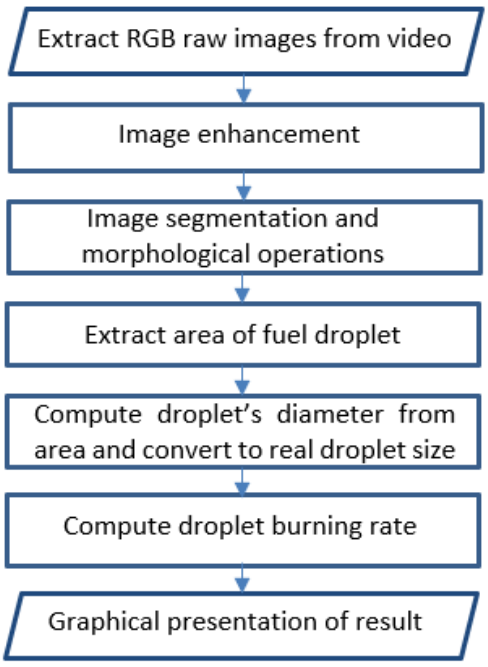

Figure 3.8: Flowchart of data analysis sequence.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Combustion of fuel droplet was conducted using the experimental designs discussed in the previous chapter. This experiment aims to investigate the combustion characteristics of biodiesel-ethanol fuel blend and palm biodiesel. Palm biodiesel is used as a reference fuel to identify the effects on combustion characteristics with addition of ethanol. In the experiment, a pure diesel droplet of approximately 2 mm in diameter was transferred onto the suspension wires. When the camera is well-positioned and ready to capture a sharp view of the droplet, the hot surface of the movable glow plug was delivered towards the droplet for ignition of the fuel droplet, and it was immediately removed from the droplet once the combustion started. Handphone camera was used in this case to record the combustion process at 120 fps with a resolution of 1920 × 1080 pixels. The whole burning process involving the combustion parameters such as droplet size evolution, burning rate and ignition delay was recorded. This chapter is dedicated to investigate these parameters in addition to the behaviour and stability of droplet throughout the burning process. The experimental findings are discussed in the following section and subsections.

4.2 Timescale Progression of Droplet Combustion

In this experiment, the burning durations of the test fuels were measured from the start of heat introduction to the droplet till the end of flame extinction, taking into consideration of the ignition delay as well. The test fuels used are B100, BE10, BE20 and BE30. The experiment was also attempted with even higher ethanol concentration with BE40 fuel, but burning does not take place on the BE40 fuel due to the highly instability of droplet upon introduction of heat, which had caused the whole droplet to rupture. From the recorded video, it is found that the whole burning process of the droplet happened within a very short time interval which is usually around 3 seconds. Figure 4.1 depicts the graph of normalized droplet area (A/A_o) against the time for all of the test fuels. From which, normalized area is the ratio of fuel's instantaneous area to its respective

initial area. From the graph, the changes of the fuel droplet's size and the droplet's behaviour can be observed. Generally, the trend shows a preheating stage before ignition and a linear decrement burning stage after the ignition point. The detailed descriptions of each stage are discussed in the following subsections.

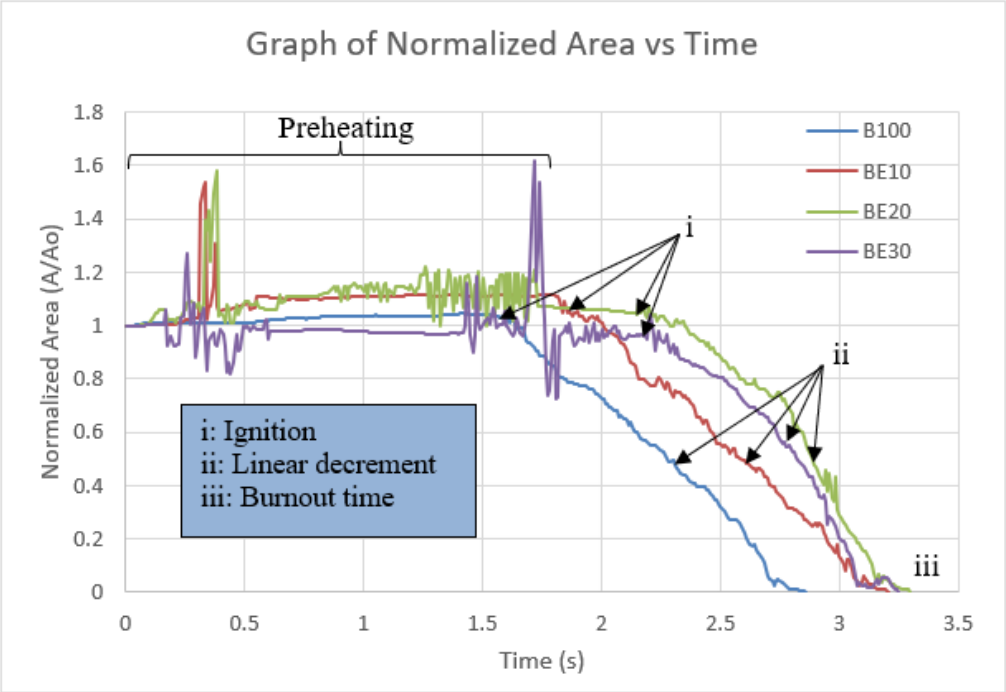

Figure 4.1: Graph of Normalized Area (A/A_o) vs Time.

4.2.1 Preheating Stage

Based on the graph in Figure 4.1, it is observed that all the fuel droplets are undergoing a preheating period before ignition. Particularly, an overall fluctuating trend can be seen in the biodiesel-ethanol fuel droplets before the droplets ignite. This fluctuating trend is attributed to thermal expansion and bubbles generation in the fuel droplet during preheating. During the preheating phase, fuel droplets are preparing themselves for ignition by absorbing heat and expand. Expansion in the droplet's size can be noticed when the normalized area is greater than one. Figure 4.2 shows the individual normalised graph for the test fuels and samples of fluctuating droplets for BE20 and BE30 to look clearer into the difference in the droplet's behaviour.

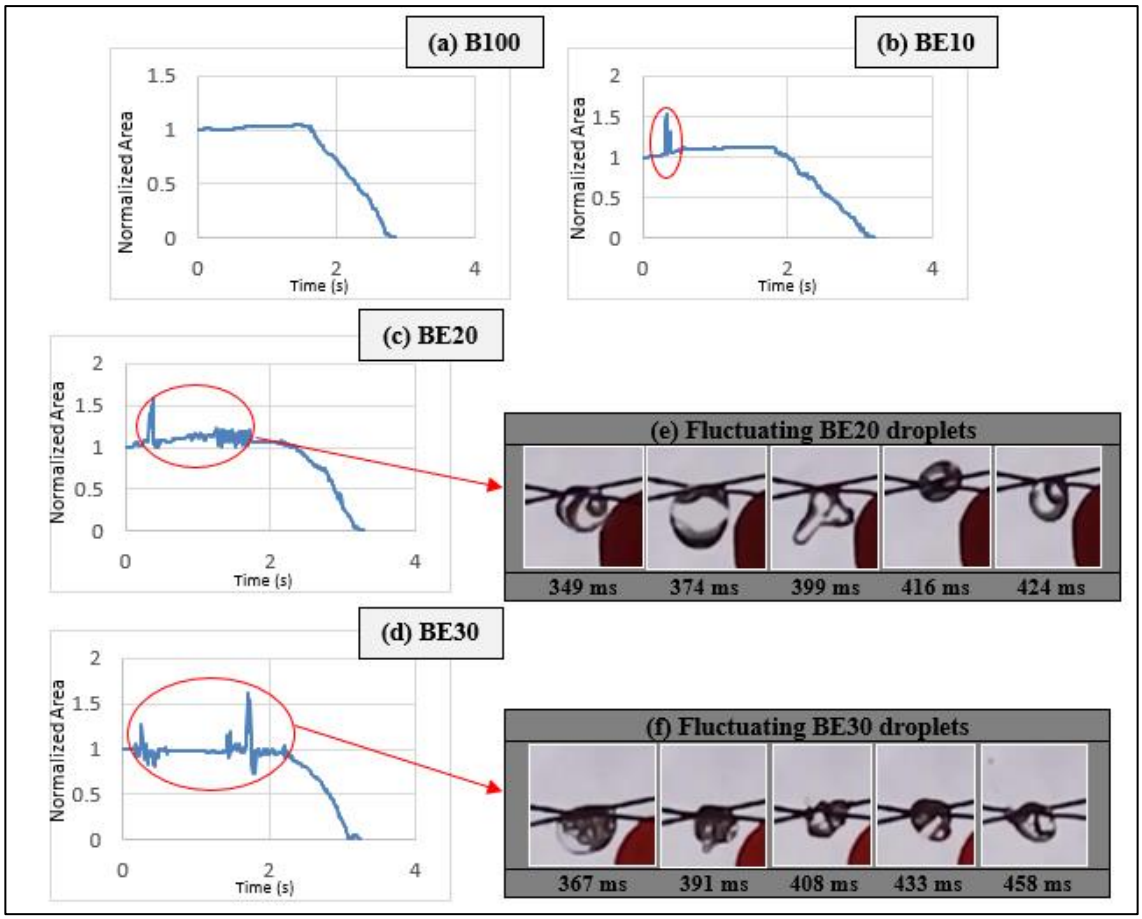

Figure 4.2: (a-d) Comparison of individual test fuel's graph of normalized area vs time and samples of fluctuating fuel droplets of (e) BE20 and (f) BE30.

From Figure 4.2(a-d), it is noticed that the B100 fuel has the smoothest trend without obvious fluctuation throughout the preheating phase, in which the graph maintains almost constant with only slight increment of the normalized area before ignition. The slight increment in droplet's size is due to the thermal expansion for the droplet to gather sufficient heat for ignition. Compared to the other test fuels, B100 shows almost no fluctuation in droplet's size during preheating due to its palm fatty acid methyl ester content, which gives rise to the high kinetic viscosity property as stated previously in the literature review. The highly viscous B100 fuel is less efficient in the air-fuel mixing process and has a lower evaporation rate (Jiang, *et al.*, 2019). For these reasons, nucleation and bubbles formation are less likely to take place in B100 fuel droplet during the burning process.

When ethanol is added to the biodiesel, droplet becomes highly unstable when heat is applied. Obvious fluctuating behaviour of biodiesel-ethanol fuel

droplet can be observed in Figure 4.2(b-d) (bounded by red circle). As the figure presents, BE30 shows the most chaotic behaviour, followed by BE20 and BE10. These excited states of the blended fuel droplets are attributed to their metastable nature which result into higher rate of nucleation as illustrated in Figure 4.2(e-f). This is agreed by the discussion of Avulapati, *et al.* (2016) for burning diesel-biodiesel-ethanol blends at various concentrations. Moreover, ethanol has a higher volatility in the BE blends compared to palm biodiesel, with a relatively greater difference in boiling points between the two components. With this huge difference in boiling point, it is expected that superheated boiling will occur within the droplet. Since ethanol has a lower boiling point, ethanol in the BE blend will vaporize first and head outward to the droplet's surface, while the biodiesel are forced to gather in the droplet's central. This causes bubbles generation and phase separation to take place between ethanol and biodiesel. Consequently, the generation of bubbles due to vaporization of ethanol results into the thermal expansion and fluctuating motion of the droplets. These effects are amplified with increasing concentration of ethanol. From Figure 4.2, there is only short fluctuation period take place in the BE10 fuel droplet, while most of the time it behaves similar to the B100 fuel droplet. With the increasing concentration of ethanol, the fluctuating period is increasing as well as the fluctuations are getting more vigorous in BE20 and BE30 fuel blends.

4.2.2 Burning Stage

Burning stage begins after the preheating stage (ignition delay) when the droplet gains sufficient heat to ignite, and it the covers range from the linear decrement trend up to the end of combustion in the graph as shown in Figure 4.1. The trend at this graph range describes that the size of the droplet decreases gradually with time till all the fuel is used up at the end of combustion. Also, in this stage, droplet fluctuations are lesser compared to the preheating phase. The combustion characteristics to be investigated during this stage include fuel droplet's size evolution, burning rate and combustion duration.

4.2.3 Micro-explosion and Droplet Puffing

Micro-explosion and droplet puffing are crucial combustion behaviour that could enhance fragmentation of fuel droplets into tiny droplets for them to burn rapidly and thus shortens the combustion duration. Also, the smaller fuel droplets can help to promote the evaporation rate and fuel-air mixing. It is usually a result of the heterogeneous nucleation that take place at the droplet surface (Yap, *et al.*, 2019).

In the present work, all of the BE blends have experienced either droplet puffing or micro-explosion, particularly the BE40 fuels which burst off due to highly intensive micro-explosion. The intensity of puffing and micro-explosion varies with the concentration of the ethanol added to the BE blends. In which, the intensity of the puffing incidents is reflected by the frequency and amplitude of the droplet size fluctuations as depicted in Figure 4.2, whereby the fluctuating trends are bounded by red circles. For instance, the intensity of puffing is in order of BE10, BE20 and BE30, whereas palm biodiesel fuel droplet did not experience any intensive droplet puffing and micro-explosion due to its highly viscous property. Yoon, *et al.* (2009) who studied on the spray characteristics of biodiesel-ethanol blended fuel, reported that the increased ethanol blending ratio will reduce the surface tension and kinematic viscosity of the biodiesel-ethanol blends which lead to its improved atomization performance. The outcomes may have an impact on the improvement of the combustion and emission properties.

Figure 4.3 depicts the droplet puffing and micro-explosion events in the blended BE fuels. For BE10 and BE20 fuels, weak droplet puffing is observed, accompanied with ejection of vapor from the droplet. When the ethanol concentration is going up, the fragmentation of fuel droplet becomes more vigorous and results into micro-explosion as shown in BE30 and BE40 fuels in Figure 4.3(c-d). For BE30 fuel, it is noticed that a sub-droplet is being detached from the main droplet body during the intensive micro-explosion, which lead to a sharp drop in the BE30 droplet's size as shown in the Figure 4.1 at around 1741 ms. Whereas for BE40 fuel, the micro-explosion is too intensive until the whole droplet ruptures. Presence of micro-explosion and droplet puffing in the BE blends are mainly because of the huge difference of boiling points between ethanol and palm biodiesel. Owing to the distinct boiling points of the two

components, superheated boiling is expected to take place when heat is applied to the BE fuel droplet, where ethanol with the higher volatility becomes superheated at first and forms bubbles to escape from the droplet. Due to the density difference, the bubbles or cavities constantly push the thin film of the droplet surface outwards from the droplet interior to the extent that the droplet's surface no longer able to withstand this force, and subsequently burst off locally due to the pressure difference. At this moment, the vapours contained within the cavities are being ejected from the droplet. Also, the depletion of ethanol from the droplet surface has altered the concentration gradient within the droplet. The change of concentration gradient has promoted an internal circulation inside the droplet, resulting to relative motion within the droplet (Shinjo, *et al*., 2014). Increasing ethanol concentration will increase the intensity of the micro-explosion as more ethanol are doing the work.

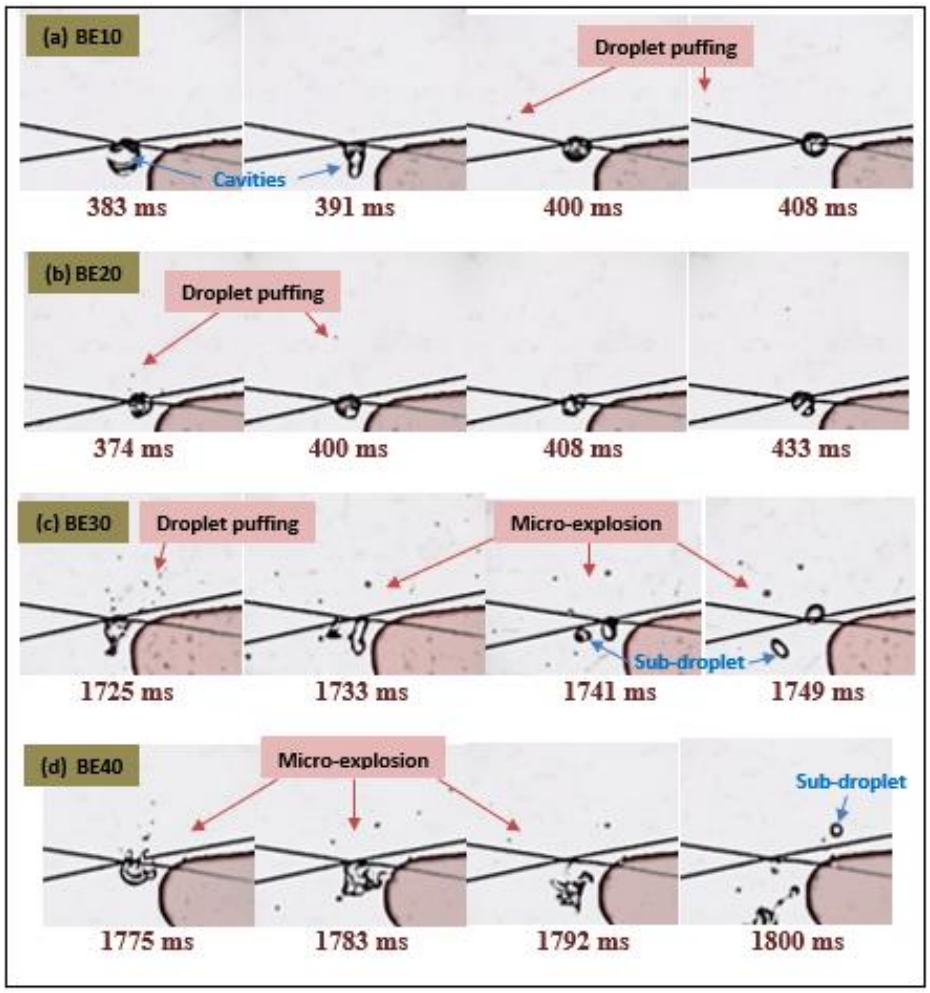

Figure 4.3: Micro-explosion and droplet puffing occurrence in BE blends.

4.3 Ignition Delay

Ignition delay is an important combustion characteristic to be studied during the preheating stage. In this study, ignition delay is the time interval between the introduction of heat to the fuel droplet and start of droplet ignition. In short, it is a preparatory period for the fuel droplet to absorb sufficient heat from the glow plug to initiate combustion. A shorter ignition delay is desired for diesel engine as it allows more diffusion burning to take place than the premixed burning throughout the combustion, leading to lower engine knock and lower NOx emissions. The result of ignition delay for all the test fuels are presented in Figure 4.4. Based on the figure, it is noticed that the increased concentration of ethanol to the blended fuels prolonged the time interval of ignition delay. B100 has the shortest ignition delay of 1.575 s, followed by BE10, BE20 and BE30 with 1.825 s, 2.167 s and 2.183 s respectively. When compared to the palm biodiesel, an increased in ignition delay can be observed in BE10, BE20 and BE30 by 15.87 %, 37.59 % and 38.60 % respectively.

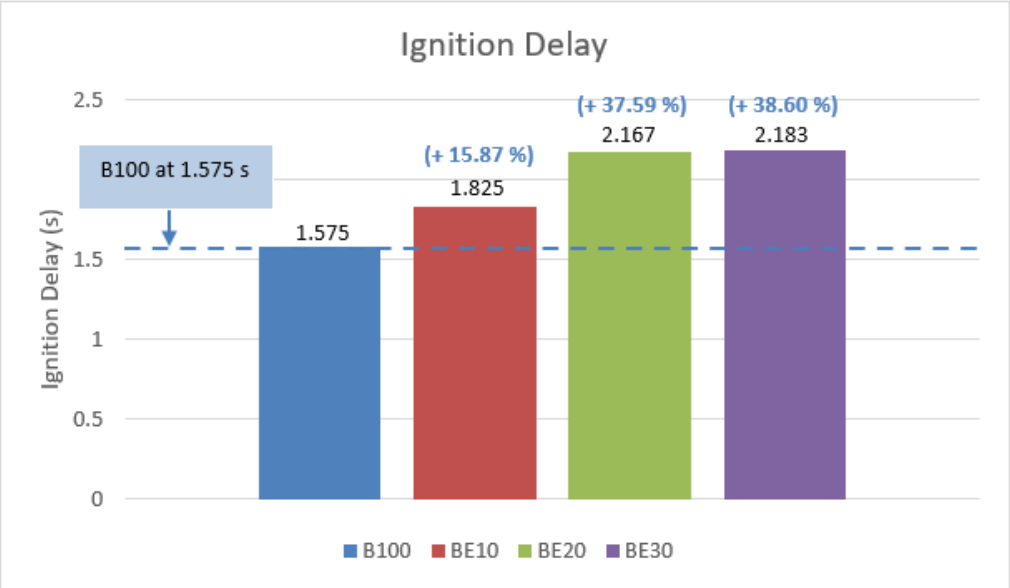

Figure 4.4: Ignition delay of test fuels.

In the case of blended BE fuels, the ignition delay increases with increasing concentration of ethanol in the blended fuels. The ignition of droplet is retarded because of lower cetane number and higher latent heat of vaporization of ethanol as compared to biodiesel. Similar findings were reported by Wei, Cheung and Ning (2018) who studied the effects of BBu and BE blends

on the combustion performance of a CI engine, whereby their results has shown that the rise in ignition delay was remarkable at high alcohol content. Wei, Cheung and Ning (2018) further reported that in practical condition, ethanol with higher latent heat of evaporation can reduce the in-cylinder temperature during the interval of ignition delay, leading to extension of ignition delay and consequently offering a greater amount of air-fuel mixture for premixed burning.

4.4 Droplet Size Evolution

Based on the trend of changing droplet size in Figure 4.1, the droplet size evolution for all the test fuels are illustrated in Figure 4.5 (for grayscale images) and 4.6 (for binary images). Variation of size of the fuel droplet with time is observed for all the test fuels.

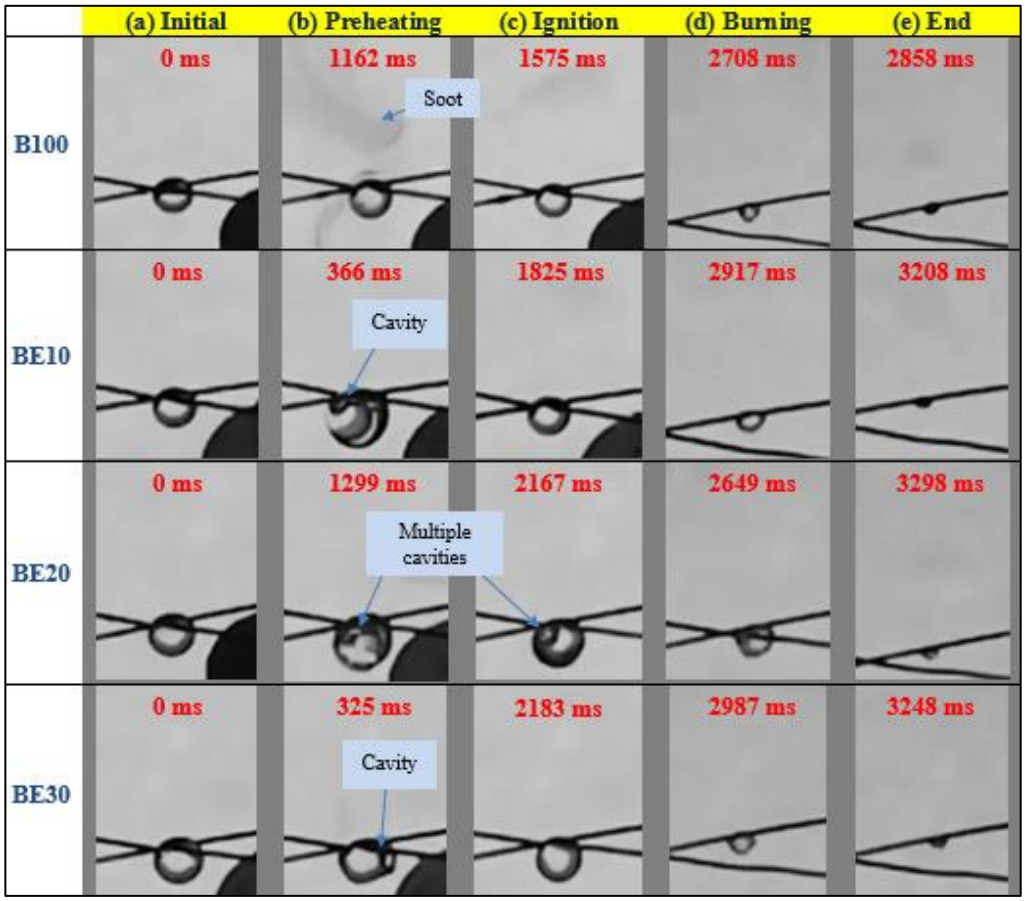

Figure 4.5: Size evolution of all test fuels' droplets in grayscale images.

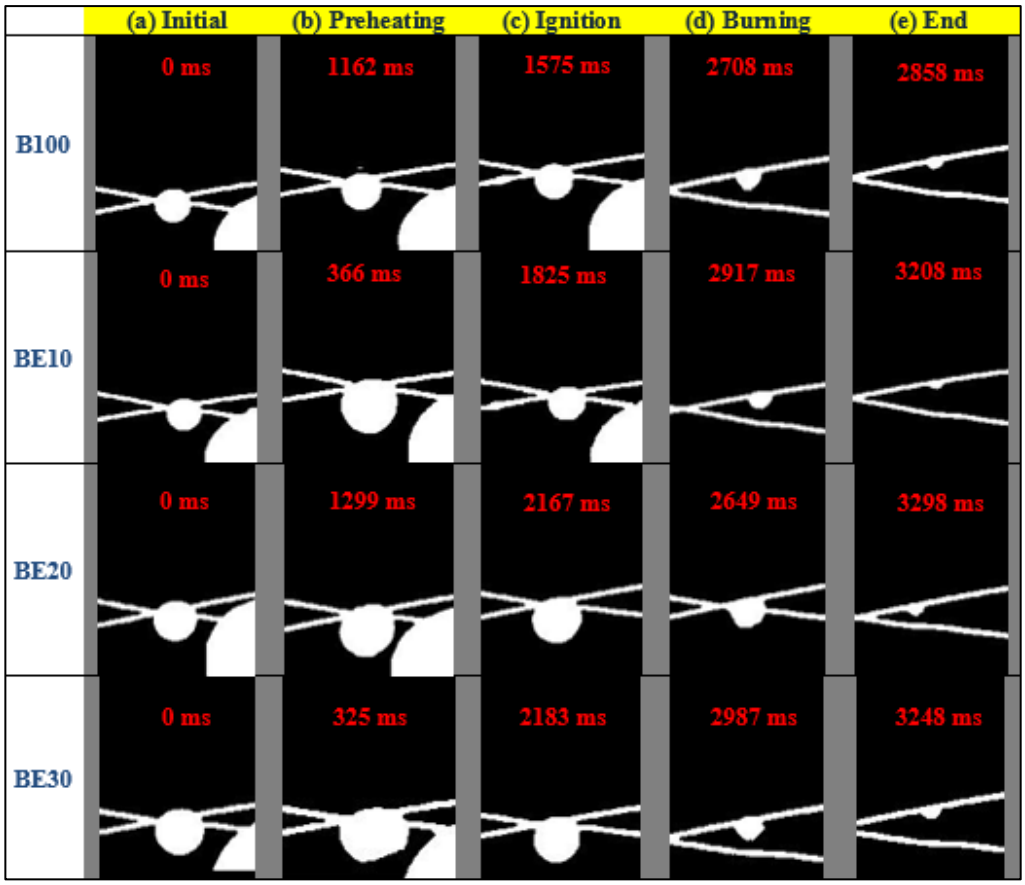

Figure 4.6: Size evolution of all test fuel's droplets in binary images.

Based on the observation, as time progresses, the droplet size expands when heat is applied to it during the preheating phase, and then reduces gradually after the ignition point and vanishes with flame extinction. The expansion in droplet size is because of the bubble growth within the fuel droplet. Yet, the droplet size expansion is very slight in the B100 fuel as compared to the BE blended fuels, with almost no bubbles formation within the B100 fuel droplet. This is due to its high kinetic viscosity property as stated previously, leading to a steady preheating phase without significant fluctuation for the B100 fuel. In contrary to the B100 fuel, cavities exist within the fuel droplets of BE blends as shown in Figure 4.5(b-c). These cavities produced are due to the reaction of the ethanol and palm biodiesel with heat, mainly because of the significant difference in boiling points between the two components. The droplet physics of the BE blends during the preheating phase were described in the previous section.

Upon ignition, the fuel droplet reacts with the oxygen in the air and produces energy in the form of light and heat. The heat dissipates through the flame to the ambient environment. The droplet's size decreases as the fuel is slowly used up for the production of energies. Aside from the energies produced, the combustion of fuel droplet is sometimes accompanied by the emission of soot as shown in Figure 4.5(b), which indicates that the combustion process is incomplete. Even though soot is sometimes produced by palm biodiesel and the BE blends due to incomplete combustion, the soot level is remarkably small when compared to the pure diesel. It is found that the burning of diesel fuel droplet constantly emits soot shortly after the ignition of fuel droplet, until the combustion ends as shown in Figure 4.7(c). This is because biodiesel and the BE blends have a higher oxygenated content than the diesel, which facilitates a more complete burning of fuel with less emission of soot. Figure 4.7(c) also illustrates flame colour and appearance of the burning diesel fuel droplet. From which, the flame of pure diesel fuel droplet combustion is bright yellow, with the presence of soot. The bright yellow flame is caused by the oxidation of soot which facilitates the effects of radiation of the flame (Yap, *et al*., 2019). Furthermore, it is also observed that the diesel fuel droplet evaporates during the combustion process, resulting in a diffusion flame configuration. Figure 4.7(a-b) shows the soot stream as well as the great amount of soot collected on the chamber cover after several burning experiment using neat diesel.

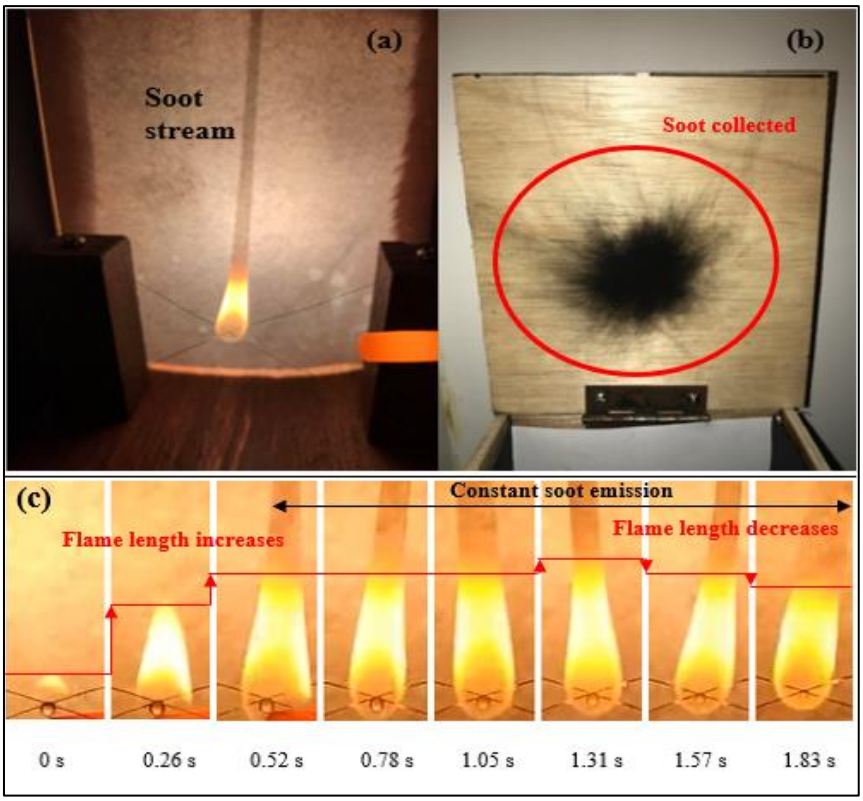

Figure 4.7: Formation of soot from burning of pure diesel fuel droplet: (a) soot stream, (b) soot collected on chamber cover and (c) constant soot emission throughout diesel droplet burning lifetime.

4.5 Burn Rate Constant

Burn rate constant is another important combustion characteristic in CI engines that decides how fast is the combustion process. In general, higher burning rate indicates a shorter combustion duration, which helps in restricting the heat losses through the wall of the combustion chamber and consequently increasing the thermal efficiency of the engine (Ooi, *et al*., 2017). The D^2 law equation was used in the analysis of the burn rate constant, regarding several assumptions that assume i) burning of fuel droplet is in a constant pressure environment, ii) fuel droplet is spherical throughout the burning life time, iii) square of the droplet diameter is linearly and inversely proportional to the time, and iv) minimal heat losses from fuel droplet to the air. The method used in the present study to analyse the burn rate constant was adopted by Ambekar, *et al.* (2014) and Ooi, *et al*. (2016) who carried out the similar experimental works. Figure 4.8 shows the D^2-t plots for all the test fuels. From which, the gradient of the graph is the burn rate constant.

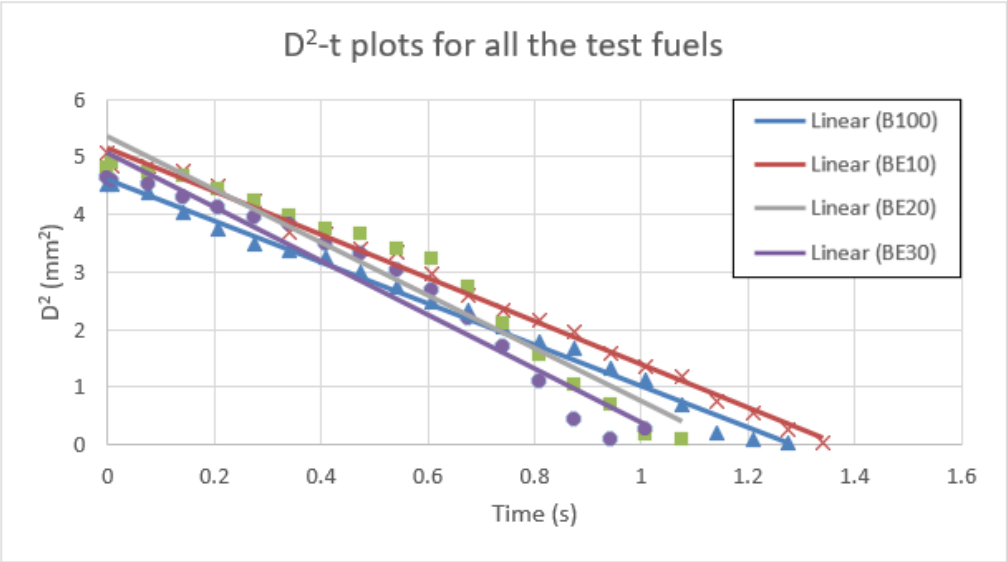

Figure 4.8: D^2-t plots for all the test fuels.

The results of the burn rate constant for all of the test fuels are shown in Figure 4.9. Based on the bar chart, it is noticed that the burn rate constant is increasing with increasing ethanol content in the BE blends. Biodiesel has the lowest burn rate constant of 3.542 mm^2/s, followed by BE10, BE20 and BE30 with a burn rate constant of 3.679 mm^2/s, 4.254 mm^2/s and 4.362 mm^2/s respectively, and an improvement of 3.87 %, 20.10 % and 23.15 % with respect to the benchmark fuel: palm biodiesel. The effect on the burning rate is less apparent in the BE10 fuel droplet, but the improvement becomes significant at 20 % and 30 % ethanol concentration due to the increasing volatility and oxygen content that promotes the combustion process (Wei, Cheung and Ning, 2018). Another factor that may contribute to the significance improvement in the burning rate is the occurrence of micro-explosion and droplet puffing which helps to minimize the droplet size by splitting out parts of the droplet from the main body.

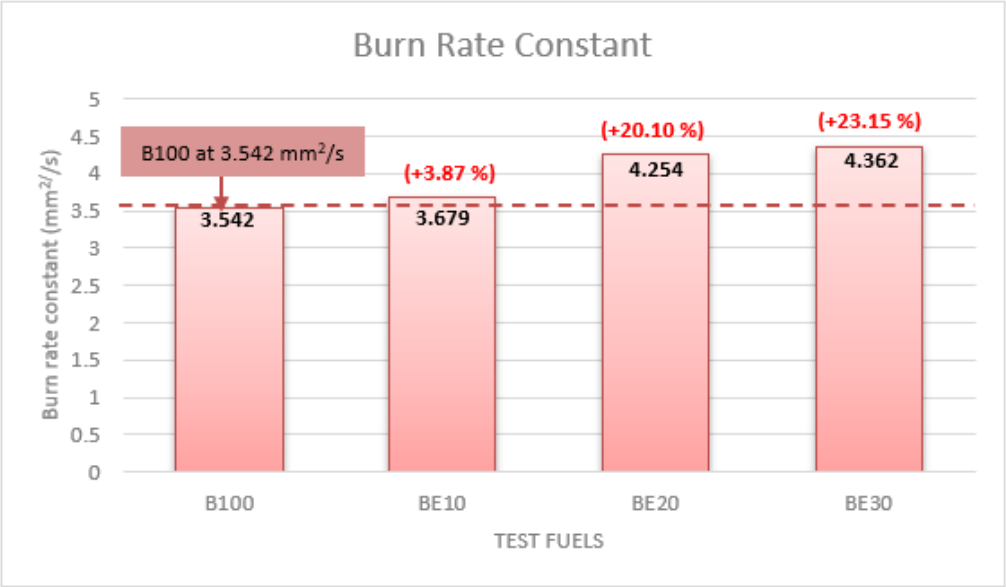

Figure 4.9: Burn rate constant for all the test fuels.

4.6 Combustion Duration

The fuel droplet burning duration has a dominant impact to the thermal efficiency of a CI engine, whereby a short burning duration is preferred as it reduces heat losses through the cylinder wall of engine, thus resulting in high thermal efficiency (Yap, *et al.*, 2019). Also, a shorter burning period prevents late combustion during the power stroke in a practical CI engine and subsequently minimizes incomplete combustion that emits harmful combustion by-products such as carbon monoxide and soot. On top of that, in terms of engine performance, reduced burning duration allows the combustion to take place near top dead centre which lead to greater in-cylinder pressure. As a result, improved output power and brake thermal efficiency can be achieved (Heywood, 1988).

In the present study, the combustion duration covers the entire burning stage and it is defined as the period starting from the ignition point till the extinction of flame. The results of combustion duration for all the test fuels are presented in Figure 4.10. Referring to the result, BE10 fuel droplet has the highest burning period of 1.375 s, which is 7.84 % higher as compared to the burning period of B100 fuel, which is 1.275 s. Whereas both BE20 and BE30 have shorter burning periods than the B100 fuel, which are 1.133 s and 1.066 s, with reduced percentages of 11.14 % and 16.39 % respectively. For the blended BE fuels, combustion duration reduces with the increasing ethanol

concentration because of the increasing oxygen content that enhances the burning process, resulting to a much quicker combustion. Additionally, micro-explosion and droplet puffing have promoted vaporization of the fuel droplets and then enhanced the mixing process of the fuel and air, resulting to a reduced burning period (Wei, Cheung and Ning, 2018). Furthermore, the significant reduced combustion duration of BE20 and BE30 may be attributed to their outstanding burn rate constant (Heywood, 1988), as well as the prolonged ignition delay for BE20 and B30 which allows sufficient time for the mixing of air and fuel, resulting to the premixed combustion mode that causes the fuels to be rapidly consumed after ignition.

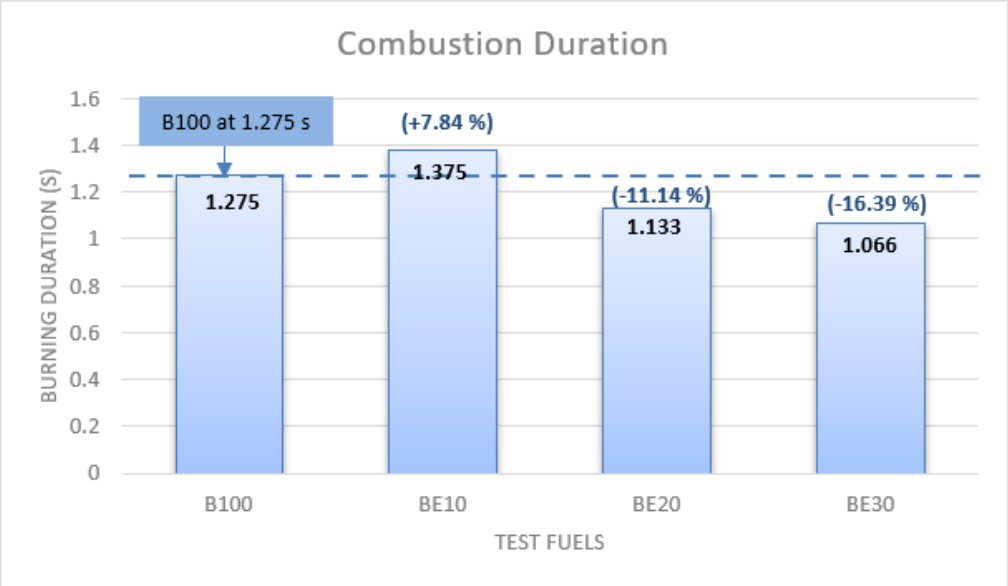

Figure 4.10: Combustion duration for all the test fuels.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The present study examined the combustion characteristics of palm biodiesel and biodiesel blended with 10 %, 20 % and 30 % by volume of ethanol. The following conclusion can be drawn, in comparison with biodiesel.

Firstly, the graph of normalized area against time has shown a generic trend for all the test fuels. Whereby the droplet burning trend starts with an expansion in size during the preheating phase and then gradually reduces its size after the ignition point till the all of the fuel is being consumed. For the blended fuels, fluctuations of the droplet size are becoming more intensified with the increasing ethanol content. The thermal expansion during the preheating phase and the droplet size fluctuations are mainly attributed to the nucleation and bubbles growth due to the distinct boiling points of the ethanol and biodiesel.

Besides, micro-explosion and droplet puffing incidents were found to be increasingly intensive with the increasing of ethanol content, owing to the relatively lower boiling point of ethanol compared to palm biodiesel, which led to occurrence of superheated boiling in the blended fuels. When ethanol is added up to 40 % concentration in the palm biodiesel, the micro-explosion event became too vigorous and caused the whole fuel droplet to rupture.

Moreover, the BE blends have shown results of prolonged ignition delay when compared to the baseline palm biodiesel during the preheating phase. In which greater ethanol content resulted into even longer ignition delay. The prolonged ignition delay is likely due to the higher latent heat of vaporization and lower cetane number of the ethanol.

Next, the BE blends have shown overall improvement in the combustion characteristics during the burning phase when compared to the baseline palm biodiesel fuel. For instance, among all the blended fuels, BE30 attained the highest burn rate constant (+23.15 % compared to palm biodiesel) and shortest combustion duration (-16.39 % compared to palm biodiesel). These are attributed to the higher oxygen content with increasing ethanol content, which promoted a cleaner and more complete combustion process.

Overall, the findings in the present study suggested that BE30 has the best combustion behaviour among all the blending ratio tested, owing to the exceptionally improved burn rate constant, combustion duration, and micro-explosion. However, the fuel gives a prolonged ignition delay as well, which is not desired in the practical applications as it will cause late combustion and thus reduces the combustion efficiency. To sum up, the findings in the report have shown the potential of ethanol to enhance the combustion characteristics of palm biodiesel. Yet, detailed and systematic research works are required to test out other potential alternative fuels and their corresponding composition with additives, for the purpose to search for the best replacement for diesel fuel in CI engines, that can deal with the environmental issues and solve the depletion crisis of the non-renewable fossil diesel.

5.2 Recommendations for future work

Still, there is room of improvements regarding the image capturing technique and the experimental setup. Improvisations can be done on the combustion chamber prototype especially on the mechanical mechanism of the movable glow plug so that it can auto ignite the fuel droplet. Even though the use of handphone camera to capture the burning process is workable, the results obtained are less favourable due to lower resolutions quality and lesser frame per second. It is advised to use a high-speed camera (with 1000 fps or more) to capture the burning process if the budget allowed to do so, so that a more precise result can be obtained.

Regarding the experimental works, it is proposed that the investigation can be conducted on temperature of the fuel droplet throughout the combustion period, to look deeper into the peak temperature, temperature at ignition point, temperature evolution during the combustion and etc. These are all related to the thermal effects in the actual practical combustion systems, particularly the cooling effects within the cylinder that may enhance volume efficiency and compression ratio of the engine and consequently produces a greater power output. Also, it is proposed that the investigation can be carried out with other blending concentrations with ethanol, or blending with another type of potential alcohol such as butanol, which has a higher cetane number, higher calorific

value and lower latent heat of evaporation than ethanol, to find out how the changes of these fuel properties can affect the combustion efficiency.

Finally, since the low boiling point, low calorific value, low caloric value and high latent heat of vaporization of ethanol can lead to combustion problems in diesel engines. It is suggested that future work can be conducted to validate the implementation of BE blended fuels in real diesel engines, with reference of the combustion parameters of the test fuels investigated in the present study. This is to study the possible problems with BE blended fuels in practical conditions so that improvement can be carried out to further enhance the fuel properties.

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APPENDICES

APPENDIX A: Tables

Table A. 1: Computation of actual initial diameter for all test fuels.

Test fuels	Area at ignition point, A (px)	Diameter, D_{im} (px): $D_{im} = \sqrt{\frac{4 \times A}{\pi}}$	Real Diameter, D_o (mm): $D_o = 0.5 \times \frac{D_{im}}{X_F}$
B100	908	34.0015	2.1251
BE10	1017	35.9845	2.2490
BE20	969	35.1251	2.1953
BE30	935	34.5033	2.1565

Table A. 2: Computation of burn rate constant for all test fuels.

Test fuels	Ignition Delay, t_i (s)	Combustion Duration, t_d (s)	Total Duration, T (s): $T = t_i + t_d$	Burn Rate Constant, K (mm^2/s): $K = \frac{{D_0}^2}{t_d}$
B100	1.575	1.275	2.850	3.5420
BE10	1.825	1.375	3.200	3.6786
BE20	2.167	1.133	3.300	4.2537
BE30	2.183	1.066	3.249	4.3624