THE EFFECT OF FUEL INJECTION PRESSURE AND IN CYLINDER TEMPERATURE ON IGNITON DELAY, COMBUSTION PERFORMANCE AND EMISSION

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" Read! In the name of Lord, Who has created (all that exists) " (Holy Quran, 96.1).
I dedicate this thesis and the journey arrive to this point to the Allah Almighty.
I could not complete this without His beneficent and merciful.

I would like to take this opportunity to thank Assoc. Professor Dr Amir Khalid as my supervisor for his support, encouragement, guidance and motivation through the years

To my all times beloved, ibu, ayah and my siblings;
for their continuous love, support and prayer.

To my beloved wife, Siti Mariam bt Basharie and our cherished sons, Adam Haikal, Aiman Syakirin, Ammar Zaqwan and Umar Kasyfi. Thank you for the love, unlimited support and encouragement.

ABSTRACT

The mixture formation prior to the ignition process plays as a key element in the diesel combustion. The objective of this research was to help an understand of the effects of air fuel mixing process during the ignition delay period and initial heat release in combustion process that strongly affects the exhaust emissions. This study investigated effects of ambient temperature,T_i and injection pressure, P_{inj} on the heat release process during ignition delay periods. Rapid compression machine (RCM) was used to simulate actual phenomenon inside the combustion chamber. This study used of 5vol%, 10vol%, and 15vol% blending of palm oil methyl ester with a standard diesel as fuels in diesel engines called as B5, B10, and B15 and standard diesel itself. The injection pressures were varied from 80 MPa to 140 MPa while an ambient temperature of RCM varied from 750 K to 950 K. For all tested fuels, the ignition delay period decreased with the increase in ambient temperature and injection pressure. The initial heat release becomes more delayed for lowering the ambient temperatures and its peak was found to increase progressively and shorten ignition delay period. Increased injection pressures make spray tip penetration longer and promotes a greater amount of fuel-air mixing occurs during ignition delay which is gives early rise of heat release rate. Higher injection rate was promoted both mixing and atomization increase heat release rate as well as shorten ignition delay. The effects of high injection and ambient temperature showed a reduction on emission, especially HC, CO and CO_2. Increased in injection pressure, leads to decrease in NO_x emission and due to superior air–fuel mixture resulting from increase in injection pressure, CO_2, CO and HC emission decreases. Higher blending ratio from B5 to B15 increases the oxygen content, which makes the combustion more complete, thus, promotes the reduction of emissions specifically for CO, CO_2, and HC, but the NOx emissions increase.

ABSTRAK

Pembentukan campuran sebelum proses penyalaan berperanan sebagai elemen penting pembakaran dalam enjin disel. Objektif penyelidikan ini adalah untuk membantu memahami kesan proses pencampuran bahan api dan udara dalam tempoh kelewatan pencucuhan dan pembebasan haba awal dalam proses pembakaran yang sangat mempengaruhi pelepasan ekzos. Kajian ini mengkaji kesan suhu persekitaran, Ti dan tekanan suntikan, Pinj terhadap proses pelepasan haba semasa tempoh kelewatan pencucuhan. Mesin pemampatan pantas (RCM) digunakan untuk mensimulasikan fenomena sebenar di dalam ruang pembakaran. Kajian ini menggunakan 5vol%, 10vol%, dan 15vol% campuran biodisel berasaskan minyak kelapa sawit dengan disel sebagai bahan api yang dipanggil B5, B10, dan B15 serta dan disel itu sendiri. Kadar tekanan suntikan adalah dari 80 MPa hingga 140 MPa manakala suhu sekitar RCM bervariasi dari 750 K hingga 950 K. Bagi semua bahan api yang diuji, tempoh kelewatan pencucuhan berkurangan dengan peningkatan suhu persekitaran dan tekanan suntikan. Pelepasan haba awal menjadi lebih lambat apabila suhu persekitaran diturunkan dan peningkatan puncak meningkat secara progresif dan memendekkan tempoh kelewatan pencucuhan. Tekanan suntikan tinggi menghasilkan penembusan hujung semburan yang panjang dan menggalakkan jumlah pencampuran bahan api yang lebih tinggi berlaku semasa proses kelewatan pencucuhan yang menyebabkan kenaikan awal kadar pelepasan haba. Kadar suntikan yang lebih tinggi telah menggalakkan proses pencampuran dan kadar pelepasan haba serta memendekkan tempoh pembakaran. Kesan suntikan tinggi dan suhu persekitaran menunjukkan penurunan pelepasan ekzos, terutama HC, CO dan CO_2. Peningkatan tekanan suntikan, menyebabkan penurunan pelepasan NOx dan disebabkan oleh campuran bahan api dan udara yang unggul akibat peningkatan tekanan suntikan, pelepasan CO_2, CO dan HC menurun. Nisbah pencampuran yang lebih tinggi dari B5 ke B15 meningkatkan kandungan oksigen yang menjadikan pembakaran lebih lengkap, oleh itu, mendorong pengurangan pelepasan khususnya untuk pelepasan NO_x, CO, CO_2, dan HC.

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LIST OF SYMBOLS AND ABBREVIATIONS

BDFs	-	Biodiesel Fuel
CME	-	Coconut Methyl Ester
COME	-	Canole Oil Methyl Ester
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
CPO	-	Crude palm oil
DI	-	Direct Injection
EGR	-	Exhaust Gas Recirculation
F	-	Fahrenheit
h	-	Coating thickness
HC	-	Hydrocabon
IC	-	Internal Combustion
ID	-	Ignition Delay
JME	-	Jatropha Methyl Ester
M	-	Molarity
NL	-	Needle lift
NOx	-	Nitrogen dioxide
^{o}C	-	Degree Celcius
P	-	Pressure
P_{inj}	-	Injection pressure
PM	-	Particulate Matter
PME	-	Palm Methyl Eester
Ra	-	Average surface roughness
RCM	-	Rapid Compression Machine
SME	-	Soybean Methyl Ester
SOI	-	Start of Injection
t	-	Time

T	-	Temperature
T_i	-	Ambient temperature
V	-	Withdrawal speed
Wt%	-	Weighted percent

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Nowadays, the price of gasoline and diesel has increased. One of the alternative fuel used for economic stability is by using biodiesel fuel. Biodiesel have become an attractive alternative to conventional diesel fuel as it helps to reduce the dependency on foreign petroleum and offers lower pollutant emissions in the present context of emission regulation. Considering all economic and environmental benefits, production of biodiesel is rapid growing as an alternative fuel of petroleum diesel around the world. Biodiesel is generally defined as ester based fuels (fatty esters) and it can be produced from various vegetable oils, waste cooking oils or animal fats through a transesterification process with alcohols such as methanol and ethanol. Biodiesel from palm oils are used in this study. Biodiesel has higher viscosity, density, flash point and cetane number compared to standard diesel fuel [1-2]. Beside this, biodiesel is nontoxic, oxygenated, biodegradable, and environment-friendly fuel.

Biodiesel fuel properties greatly influence the engine performance, emissions characteristics and lead the differences in combustion behaviors [3–5]. In several conditions, the fuel properties of biodiesel may be changed when different stocks are used. Biodiesel offer several advantages over petroleum fuel, such as bio-diesel provides smoother engine operation by enhancing better lubricity and better combustion characteristics. Biodiesel has some disadvantages, such as the production cost of biodiesel is higher than standard diesel a major barrier to its commercialization. Biodiesel can significantly reduce green house gas emission to the atmosphere by reducing CO, unburned hydrocarbon and particulate matters, however biodiesel produces higher nitrous oxide emissions which are becoming more strictly regulated green house gas around the world [6].

Despite years of improvement attempts, BDFs engines still have problem of emitting NO_x and Particulate Matter (PM) into the atmosphere because of the oxidation stability, cetane number, stoichiometric point, bio-fuel composition and antioxidants on the degradation extremely viscous [7]. The increase in NO_x emissions might be an inherent characteristic of BDF, because the level of saturation is known to affect the cetane number and higher oxygen contents, which can affect NO_x production. Thus, the improvement of emissions exhausted from BDFs engines is urgently required to meet the future stringent emission regulations. Generally, BDFs combustion is by nature heterogeneous combustion [8]. NO_x is formed at high temperature and stoichiometric mixture region; on the other hand, PM is emitted at rich region. It is known that, control the mixture formation in the diesel engine is necessary to improve exhaust emissions [9]. In particular, mixture formation during early stage of burning is important process because ignition is controlled by physical process caused by multi-hole injection and air motion and chemical process of fuel decomposition and oxidation [10].

The alternative combustion strategies with systematic control of ambient temperature and oxygen concentration have provided new opportunities and considerable improvement in the combustion process and exhaust emissions reduction. An Internal Combustion (IC) engine refers to an engine which the heat transfers to the working fluid occurs within the engine itself, usually by the combustion of fuel with an oxidizer. The combustion characteristics of direct-injection diesel engines are determined by many factors such as the atomization of a spray, the fuel evaporation and the air-fuel mixing rate [11]. This combustion condition leads to highest possible peak temperatures and the highest possible thermal efficiencies [12].

Ishiyama et al. [13] reported that, in diesel combustion, fuel gasification, thermal cracking and oxidation process begin at early time during ignition delay period. The authors reported the concepts of the evaporation of spray droplets and atomization of a spray. In the report, it was suggested that mixture is first formed at spray boundary at middle stream of the spray [14]. It was reported that the implementation of boost pressure, swirl velocity and injection pressure has a great effect on the mixture formation, ignition delay, turbulence, ambient density and ambient pressure, then, affects to the flame propagation, combustion characteristics and emissions elements [15]. Although some results have been reported to improve emissions by the concept of improving mixing, it is necessary to analyze the effect of every design parameter on mixture formation and combustion in detail. It is suggested that there is optimum relation between spray momentum and air motion caused by design parameters [16]. It is necessary to make clear the relation between combustion characteristics and physical phenomena such as air entrainment and mixing ratio.

In this study the effect of injection pressure and variant ambient temperature towards the ignition delay period and emission during combustion was investigated in the rapid compression machine (RCM). A constant volume chamber is an excellent tool to study the influence of temperature on auto ignition of combustible mixtures as it gives direct measure of ignition delay [17]. In diesel engine, ignition delay is a major factor determining the rapid pressure rise in the initial burning stage and the subsequent combustion stages. The ignition delay, which is defined as the time between the start of fuel injection and the start of the combustion, also influences the combustion process strongly. The ignition delay in a diesel engine is generally seen as consisting of two different phases which are the physical and chemical ignition delay [18]. Physical ignition delay corresponds to the mixture formation, and the chemical delay to the time necessary to get an exponential increase in the chemical reaction rate. The physical processes involved such as atomization, penetration, air entrainment and vaporization and the chemical processes such as fuel decomposition and accumulation and oxidation [19]. In a research done by Yiming Wang et. al. [20] on a study of the combustion phenomena under high temperature using constant volume chamber has concluded that at high temperature the ignition delay becomes very short and the ignition occurs near the nozzle tip and the combustion duration was prolonged. The effects of temperature on ignition process are investigated up to the initial stages of pressure rise, which occurred as a result of net heat release due to evaporation of fuel and heating [21].

The influence of the injection pressure inside the combustion chamber has to be considered in the analysis of spray formation and propagation [22]. The flame behavior and turbulence intensity in the combustion field may play an important role, and it is important to clarify these flow characteristics for a better understanding of the mechanism of combustion improvement with high pressure injection [23–25]. Combustion in diesel engines is controlled mixing and the swirl combined with high injection pressure to the inlet air assists in faster air fuel mixing and better combustion. This, combined with high injection pressures, further increases the combustion efficiency [26]. High pressure fuel injection induces a higher level of dispersion of the fuel with better atomization and fuel-air mixing. The aim of the fuel injection process in a diesel engine is the preparation of a fuel-air mixing to achieve a clean and efficient combustion process. High pressure injection was also expected to result in improvements in exhaust odor.

Spray penetration and fuel distribution should be carefully investigated in order to study the effect of the high injection pressure spray. For these times, these investigations are more focused on fuel injections and alternative fuel usage. The objective of this research is to help an understanding of the effects of mixture formation during the ignition delay period on ignition and initial heat release in diesel combustion that strongly affects the exhaust emissions. The research was to investigate the effects of variant ambient temperature and injection pressure into the spray on the heat release process during ignition delay periods. In-cylinder, pressure recovery, heat release analysis and observations of mixture formation are employed to study influences of these parameters on the combustion process and exhaust emissions. Hopefully with this study, it gives a lot of help to understand the problem that faced during the development process also improving the entire of combustion process.

Biodiesel based on palm oil production was programmed from 1982 to reach the use of B5 (5% palm oil and 95% diesel) blend for Malaysian industries and vehicles. For the beginning stage, Malaysia government has launched its first biodiesel blend with petroleum diesel known as B5 with commercial name named as Envo Diesel [27-28]. Among government agencies that involved in the biodiesel programme were Ministry of Defence, Ministry of Plantation Industries and Commodities, Kuala Lumpur City Council and Public Work Department of Selangor [29].

In addition, Malaysia Government under Ministry Plantation Industries and Commodities has initiated the National Biofuel Policy (NBP) along with the official launching of Envo Diesel in 2006. The most important policies of NBP were palm oil promotion as a biofuel in order to substitute conventional fuels [30]. The objectives of this policy are to produce the biofuels for the transportation and power generation, exporting the biofuel to Europe and commercialising the biofuel technology for the domestic implementation. The detailed objectives are paralleled with the Five-Fuel Diversification Policy that encouraged the use of biofuel for energy sector and transportation. Furthermore, those policies were drafted to ensure the biofuel will be retained as one of the five energy sources for the country. Other primary purposes of the instigated policy are; to promote the palm oil for the domestic and abroad market, to diminish the dependency of the crude oil depletion, plus to stabilise the commodity at the par price.

There are five strategic thrusts under the NBP which are biofuels specifically for transport, industry, technologies, export and cleaner environment. There were action plans for short, medium and long terms that coordinated with the current implemented policies. By early 2008, the policy implementation stages are expected to be nationwide with the support from the Ministry of Plantation Industries and Commodities along with Malaysia Palm Oil Board (MPOB) [31].

The mandatory blending of B5 was implemented in stages beginning 2011 and it was extended to B7 by the end of 2014. The government also implemented the B10 in 2018 and also scheduled to implement the B20 in the year 2020 following the success of the B5, B7 and B10 implementation. The biodiesel mandate had a positive effect on domestic demand of Malaysian palm oil. It show the government's commitment in using palm biodiesel locally as a renewable energy that contributes to a cleaner environment [32].

1.2 Problem Statement

The major problem in diesel combustion chamber design is to understand the important of phenomenon of the interaction between fuel spray and surrounding gas prior to ignition. During this period, combustible mixture spontaneous ignition since the air temperatures are above the fuel ignition point and occurs within delay period after fuel injected. There are many studies on the fuel-air premixing that responsible to the ignition of diesel spray which linked to the improvement of exhaust emission [33–35] In particular, mixture formation during ignition delay period is important process because ignition is controlled by physical process caused by injection pressure , air motion, and chemical process of fuel decomposition and oxidation. The injected fuel sprays needs to be finely dispersed to evaporate and mix readily. The most important issue in diesel combustion is achieving sufficient rapid mixing between the injected fuel and the air in cylinder prior to ignition. Therefore, the examination of the first stage of mixture formation is very important consideration due to the fuel-air premixing process linked with the combustion characteristics.

Based on the above, Authors have started research to investigate mixture formation focusing on ignition delay period [24][36–39]. In this study, the new combustion concept based on the characteristics of diesel ignition and combustion is investigated focusing on fuel-air mixing with changing ambient condition and injection parameters. Experimentally, it is known that ignition delay (ID) decreases with an increase in several parameters such as cetane number, ambient temperature and injection pressure. In diesel engines, combustion process and exhaust emissions are more clearly observed by examining the characteristics of the evaporation of fuel spray and initial heat recovery process during the ID period. Physical characteristics that affect the advancement of the air fuel mixing and the fuel spray will influence the ID. As the cost of diesel fuel increases and emission standards become more stringent, there is a requirement to decrease emissions and to enhance the efficiency of diesel engines. Therefore, the study of the combustion characteristics of diesel and blended biodiesel fuels is an essential topic of research. The intent of the present study was to tentatively examine the effect of injection pressure and ambient temperature inside the combustion chamber on ID, heat release and emissions of diesel and blended biodiesel fuels.

1.3 Objectives

This research embarks on the following objectives:

i. To help an understanding of the effects of mixture formation during the ignition delay period on ignition and initial heat release in diesel combustion.
ii. To analyze the effect of ambient temperature and injection pressure on ignition delay, heat release and emissions.
iii. To compare the combustion characteristics of diesel and bio-diesel that will be used to fundamental understanding in combustion strategies.

1.4 Scopes of Study

The scope of this study were :

i. This study investigated biodiesel combustion fundamentally using a rapid compression machine (RCM) to simulate actual phenomenon inside the combustion chamber
ii. The experiment parameters and physical factors during experiment are ambient temperature and injection pressure.
iii. The ambient temperatures are set to 750 K, 850 K, and 950 K.
iv. The injection pressures are set to 80 MPa, 90 MPa, 130 MPa and 140 MPa

1.5 Significance of Study

The alternative combustion strategies with systematic control of mixture formation have provided new opportunities and considerable improvement in the combustion process and exhaust emissions reduction The major problem in diesel combustion is to understand the importance of the phenomenon of the interaction between fuel spray and surrounding gas prior to ignition. Therefore, the investigation of the first stage of mixture formation is essential due to the fuel-air premixing process linked with the combustion characteristics. In particular, mixture formation during ignition delay period is an important process because the ignition is controlled by physical process caused by air motion, and chemical process of fuel decomposition and oxidation. The combustion concept based on the characteristics of diesel ignition and combustion is investigated focusing on fuel-air mixing with changing ambient conditions and injection parameters. The study on the mixture formation and combustion process were performed in RCM. RCM is an instrument designed to simulate the actual phenomenon of a single compression event of an engine cycle of an internal combustion engine.

1.6 Thesis Outline

This thesis is arranged into five major chapters. Chapter One is the introduction in which the problem statement, objectives and scope of research, contribution to the knowledge in research work are presented. The literature review is presented in Chapter Two and covers topics from the basic of spray, ignition and combustion process in RCM as well as emission characteristics by using different blended biodiesel fuels. In Chapter Three, detail description of the experimental setup, procedures and techniques. An overview is presented of the combustion analysis methods and ignition delay definitions are described in detail. All experimental results are presented and discussed with evidence to support them are presented in Chapter Four. Finally, Chapter Five summarizes of conclusions drawn from the research work conducted and recommendations for future works are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Diesel engines are the most important power source in the heavy transport sector and off-road machinery, and they are increasing their presence in the light and passenger transport too. In a diesel engine, combustion and emission characteristics are significantly influenced by spray atomization and fuel-air mixing processes in the combustion chamber [40].

A rapid compression machine (RCM) is an excellent tool to clarify the effect of the air-fuel ratio, injection pressure, and compression temperature on ignition delay and NO_x emissions. It also able to study the effect of temperature on the auto-ignition of combustible mixtures because it provides a direct measure of the ignition delay [41]. When there is a net heat release due to fuel evaporation and heating, the effect of temperature on the ignition process being investigated until early pressure rise. The interaction between fuel spray and surrounding gas is important for the combustion efficiency and exhaust emissions [42]. The RCM was applied in order to keep the wide observation region [43]. A number of researchers were conducted the experiments to study on the mixture formation and combustion process was performed in RCM [45-46].

2.2 Ignition Delay

In diesel engine, ignition delay is a major factor determining the rapid pressure rise in the initial burning stage and the subsequent combustion stages. The ignition delay, which is defined as the time between the start of fuel injection and the start of the combustion, also influences the combustion process strongly. The ignition delay in a diesel engine is generally seen as consisting of two different which is the physical and the chemical ignition delay [47]. Physical ignition delay corresponds to the mixture formation, and the chemical delay to the time necessary to get an exponential increase in the chemical reaction rate. The physical processes involved such as atomization, penetration, entrainment and vaporization and the chemical processes such as fuel decomposition and accumulation and oxidation [48].

A typical pressure trace got during one such test run has shown on Figure 2.1, when the piston was released, the gaseous mixture is isentropically compressed to P_2. And when the piston was sparked event is sequenced 20 to 30 ms following end of compression, there has a little pressure was decreased resulting from heat transfer to the combustion chamber walls, (P_2 –P_2’) that was called ignition delay times (t_1 and t_2) [49]. For t_1 (physical delay) is the period of time from the start of injection to when the piston pressure for a acting spray separates from that of an identical spray injected into an inert nitrogen atmosphere. The period time from t_1 to continuous pressure curve cross the dated straight line is time t_2 (chemical delay) that represents the heat loss from the combustion chamber. The combination from t_1 + t_2 is defined as the ignition delay time that is used to characteristics diesel fuel. Fuel is injected into high temperature and high pressure air condition, when the pressure rise the ignition start to reduce, cracking and gasification is observed heat loss from surrounding air [50].

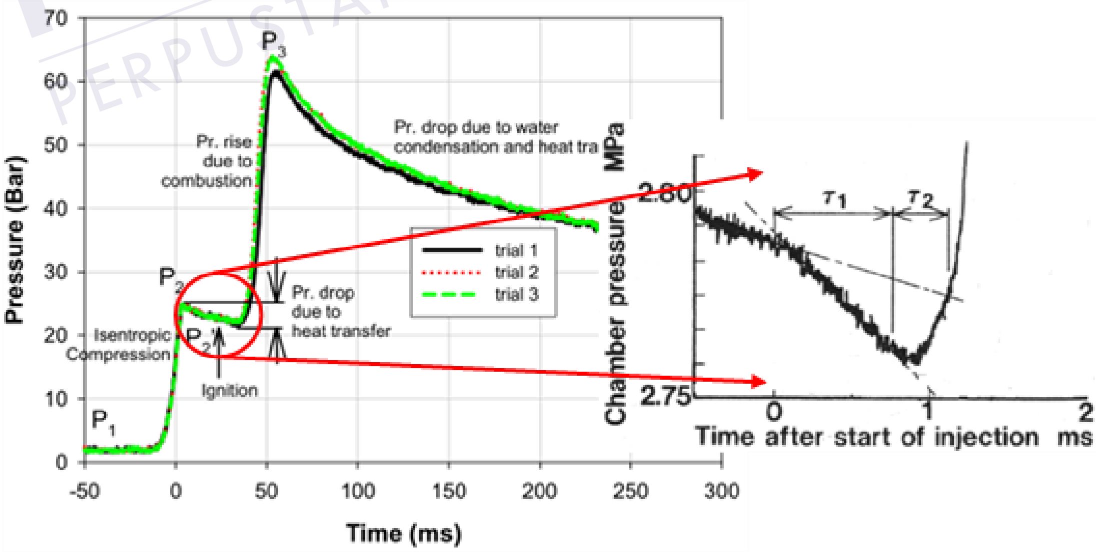

Figure 2.1: Time history of pressure in combustion chamber [49]

Direct injection (DI) diesel engines are used worldwide because of their high efficiency [45]. However, the main problems associated with diesel engines are the high level of NO_x and particulate emissions. According to Breda Kegl [51], NO_x emissions are significantly affected by injection timing and injection pressure. High pressure fuel injection induces a higher level of dispersion of the fuel with better atomization and fuel-air mixing. The aim of the fuel injection process in a diesel engine is the preparation of a fuel-air mixing to achieve a clean and efficient combustion process [52]. A comparative analysis was made by N.A.Henein between the effects of increasing the fuel injection pressure and swirl ratio on the auto ignition reactions, cool flames and premixed combustion fractions [53]. Significant reductions in particulate matter (PM) and smoke emissions from DI diesel engines with high pressure injection have been reported [54]. High pressure injection was also expected to result in improvements in exhaust odor.

Experimental study was conducted by Casey M. Allen et al in RCM using biodiesel and diesel fuels with different oxygen concentration, XO_2 as shown in the Figure 2.2 : Comparison of ignition delay period, τ for BDFs and diesel fuel [55]. Results implied that the disparity between the two fuels grows and the biodiesel measurements are shorter than the diesel measurements by 3.0 ms (-23%) and 2.3 ms (-23%) at XO_2 = 0.12 and 0.18, respectively [55]. The fuel kinetics play an increasingly important role at lower temperatures but that, at higher temperatures, at first ignition delay period may be dominated by physical transport process. A longer total ignition delay period for diesel fuel is consistent with this expectations based on the reported cetane number for the fuels. The cetane number for typical biodiesel has higher than the typical diesel fuels [56]. This is reducing the size of premixed combustion and thus shorten the ignition delay. Normally if the ignition delay is shorter under the same experimental condition, biodiesel starts the combustion process earlier than diesel and therefore the temperatures and pressures inside the cylinder will be lowered during the combustion. Zhang et al [57] studied the ignition delay in the shock tube with the variation of the pressure and equivalence ratio were found that an increase in the pressure results in a decrease in the measured ignition delay times. The observed trends in reactivity with pressure were very similar for all equivalence ratios in their study.

Figure 2.3 shows the effect of ambient pressure on ignition delay, τ. According to the figure, increasing ambient gas pressure will results in shortens ignition delay because of the better mixing achievable at higher injection pressures. Beside that by

REFERENCES

[1] A. Datta and B. K. Mandal, "A comprehensive review of biodiesel as an alternative fuel for compression ignition engine," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 799–821, 2016.

[2] C. Wityi *et al.*, "Ignition and combustion characteristics of various biodiesel fuels (BDFs)," *Fuel*, vol. 158, pp. 279–287, 2015.

[3] A. N. Ozsezen and M. Canakci, "Determination of performance and combustion characteristics of a diesel engine fueled with canola and waste palm oil methyl esters," *Energy Conversion and Management*, vol. 52. pp. 108–116, 2011.

[4] M. Suresh, C. P. Jawahar, and A. Richard, "A review on biodiesel production , combustion , performance , and emission characteristics of non-edible oils in variable compression ratio diesel engine using biodiesel and its blends," *Renew. Sustain. Energy Rev.*, vol. 92, no. April, pp. 38–49, 2018.

[5] A. S. Yusuff, O. D. Adeniyi, M. A. Olutoye, and U. G. Akpan, "Performance and Emission Characteristics of Diesel Engine Fuelled with Waste Frying Oil Derived Biodiesel-Petroleum Diesel Blend," *Int. J. Eng. Res. Africa*, vol. 32, pp. 100–111, 2017.

[6] P. Mccarthy, M. G. Rasul, and S. Moazzem, "Analysis and comparison of performance and emissions of an internal combustion engine fuelled with petroleum diesel and different bio-diesels," *Fuel*, vol. 90, no. 6, pp. 2147–2157, 2011.

[7] I. Miyata, Y. Takei, K. Tsurutani, and M. Okada, "Effects of Bio-Fuels on Vehicle Performance : Degradation Mechanism Analysis of Bio-Fuels Reprinted From : Alternative and Oxygenated Fuels," *SAE Pap. No. 2004-01-3031*, 2004.

[8] J. Senda, N. Okui, T. Suzuki, and H. Fujimoto, "Flame Structure and Combustion Characteristics in Diesel Combustion Fueled with Bio-diesel," *SAE Pap. 2004-01-0084*, 2004.

[9] A. Khalid, T. Yatsufusa, T. Miyamoto, J. Kawakami, and Y. Kidoguchi,

"Analysis of Relation between Mixture Formation during Ignition Delay Period and Burning Process in Diesel Combustion," *SAE Pap. No. 2009-32-0019*, 2009.

[10] W. Jazair, T. Harada, S. Kubo, Y. Kidoguchi, and K. Miwa, "Improvement of Emissions in a DI Diesel Engine Fuelled by Bio-diesel Fuel and Waste Cooking Oil," *SAE Pap. No 2007-01-2029*, Jul. 2007.

[11] A. Adam, N. Inukai, Y. Kidoguchi, K. Miwa, and S. Miyashiro, "A Study on Droplets Evaporation at Diesel Spray Boundary During Ignition Delay Period," *SAE 2007-01-1893*, 2007.

[12] L. M. Pickett, S. Kook, and T. C. Williams, "Visualization of Diesel Spray Penetration, Cool-Flame, Ignition, High-Temperature Combustion, and Soot Formation Using High-Speed Imaging," *SAE Pap. No 2009-01-0658*, pp. 439–459, Apr. 2009.

[13] T. Ishiyama, K. Miwa, and O. Horikoshi, "A Study on Ignition Process of Diesel Sprays," *JSME Int. J.*, vol. 38, 1995.

[14] Kidoguchi, "A Study on Multi-hole Spray Interference and Mixture Formation in Diesel Combustion," *Trans JSAE 39-3*, pp. 137–143, 2008.

[15] Amir Khalid, "A Study on Effects of Mixture Formation on Ignition and Initial Heat Release of Diesle Spray," University of Tokushima, 2011.

[16] T. Yatsufusa, "Effects of Supercharging, Swirl Strength and Fuel Injection Pressure on Development and Combustion of Diesel Spray," *Trans JSAE 40-3*, 2009.

[17] M. Ikegami, K. Miwa, and M. Inada, "A Study on Ignition and Combustion of a Diesel Spray by Means of a Rapid Compression Machine," *Bull. JSME*, vol. 24 No 195, 1981.

[18] E. Rosseel and R. Sierens, "The Physical and the Chemical Part of the Ignition Delay in Diesel Engines," *SAE Pap. No. 961123*, 1996.

[19] F. E. Corcione, B. M. Vaglieco, G. Valentino, and I. Motori, "A Study of Physical and Chemical Delay in a High Swirl Diesel System via Multiwavelength Extinction Measurements," *SAE Pap. No. 980502*, no. 724, 1998.

[20] Y. Wang, C. Yang, and G. Shu, "An Observation of High Temperature Combustion Phenomenon in Low-Heat- Rejection Diesel Engines," *SAE Pap. No 940949*, no. 412, 1994.

[21] G. R. Kannan and R. Anand, “Effect of injection pressure and injection timing on DI diesel engine fuelled with biodiesel from waste cooking oil,” *Biomass and Bioenergy*, vol. 46, pp. 343–352, 2012.

[22] N. Jaat, A. Khalid, B. Manshoor, and Him Ramsy, “Review of the investigation of mixture formation and combustion process using rapid compression machine and direct visualization system,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 50, 2013.

[23] I. Yamaguchi, T. Nakahira, and M. Komori, “An Image Analysis of High Speed Combustion Photographs for DI Diesel Engine with High Pressure Fuel Injection,” *SAE Pap. No 901577*, 1990.

[24] N. Jaat, Amir Khalid, A. Rhaodah, S. Azwan, M. Azahari Razali, and M. Basharie, “Effects of ambient temperature and injection pressure on biodiesel ignition delay,” *J. Mech. Sci.*, vol. 11, no. 2, pp. 2723–2733, 2017.

[25] N. Jaat, A. Khalid, N. Mustaffa, and Abd Fathul Hakim Zulkifli, “Analysis of Injection Pressure and High Ambient Density of Biodiesel Spray using Computational Fluid Dynamics,” *Penerbit Akad. Baru*, vol. 11, no. January, pp. 28–39, 2019.

[26] K. K. Rao, D. E. Winterbone, and E. Clough, “Influence of Swirl on High Pressure Injection in Hydra Diesel Engine,” *SAE Pap. No. 930978*, no. 412, 1993.

[27] M. Faizal and S. Ateeb, “Energy , Economic And Environmental Impact Of Palm Oil Biodiesel In Malaysia,” *J. Mech. Eng. Res. Dev.*, no. September, pp. 93–96, 2018.

[28] M. H. Ong HC, Mahlia TMI, “A review on energy pattern and policy for transportation sector in Malaysia,” *Renew Sustain Energy Rev*, vol. 16, pp. 532–542, 2012.

[29] M. H. Mat Yasin, R. Mamat, G. Najafi, O. M. Ali, A. F. Yusop, and M. H. Ali, “Potentials of palm oil as new feedstock oil for a global alternative fuel: A review,” *Renew. Sustain. Energy Rev.*, vol. 79, no. May, pp. 1034–1049, 2017.

[30] S. Lim and K. T. Lee, “Implementation of biofuels in Malaysian transportation sector towards sustainable development : A case study of international cooperation between Malaysia and Japan,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 4, pp. 1790–1800, 2012.

[31] a. Z. Abdullah, B. Salamatinia, H. Mootabadi, and S. Bhatia, “Current status and policies on biodiesel industry in Malaysia as the world’s leading producer

of palm oil," *Energy Policy*, vol. 37, no. 12, pp. 5440–5448, 2009.

[32] B. Nambiappan *et al.*, "Malaysia : 100 Years of Resilient Palm Oil Economic Performance," *J. Oil Plam Resesarch*, vol. 30, no. March, pp. 13–25, 2018.

[33] A. K. Agarwal *et al.*, "Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics," *Energy Convers. Manag.*, vol. 91, pp. 302–314, 2015.

[34] M. Badami, P. Nuccio, G. Trucco, and P. Torino, "Influence of Injection Pressure on the Performance of a DI Diesel Engine with a Common Rail Fuel Injection System," *SAE 1999-01-0193*, 1999.

[35] D. Ag, T. Engine, and D. Dep, "Effect of Injection Pressure on the Performance Duty DI Diesel Engine," vol. 2003, no. 724, 2003.

[36] M. Jaat, A. Khalid, B. Manshoor, S. M. Basharie, and H. Ramsy, *Review of the investigation of fuel-air premixing and combustion process using rapid compression machine and direct visualization system*, vol. 465–466. 2014.

[37] N. Jaat, K. Amir, R. Him, and M. Bukhari, "An Analysis of the Ambient Condition Effect on Biodiesel Spray Using Constant Volume Chamber," *Appl. Mech. Mater.*, vol. 663, pp. 3–7, 2014.

[38] N. Jaat, "Influences of the end of injection and ambient temperature on biodiesel combustion," vol. 11, no. 3, pp. 2883–2894, 2017.

[39] A. Khalid, R. S. Nursal, D. W. Jacob, N. Jaat, N. M. Sunar, and S. H. Amirnordin, "Effect of ambient temperature on ignition delay, combustion process and emission of biodiesel derived from algae," *Int. J. Integr. Eng.*, vol. 10, no. 4, pp. 43–48, 2018.

[40] C. Series, "Investigation of Combustion Process of Biodiesel Derived from Waste Cooking Oil , Jatropha , Palm Oil and Algae using Rapid Compression Machine Waste Cooking Oil , Jatropha , Palm Oil and Algae using Rapid," *J. Phys. Conf. Ser.*, 2018.

[41] A. Khalid, K. Hayashi, Y. Kidoguchi, and T. Yatsufusa, "Effect of Air Entrainment and Oxygen Concentration on Endothermic and Heat Recovery Process of Diesel Ignition," *SAE 2011-01-1834*, pp. 1–5, 2011.

[42] Amir Khalid, "Effect of Ambient Temperature and Oxygen Concentration on Ignition and Combustion Process of Diesel Spray," *Asian J. Sci. Res.*, vol. 6, no. 3, pp. 434–444, 2013.

[43] Mittal G, “A Rapid Compression Machine - Design, Characterization and Auto Ignition Investigations,” Case Western Reserve University, 2005.

[44] T. Shiozaki, H. Nakajima, H. Yokota, and A. Miyashita, “The Visualization and Its Analysis of Combustion Flame in a DI Diesel Engine,” *SAE Pap. No. 980141*, no. 724, 1998.

[45] H. Takahashi, K. Tomaru, and S. Shiga, “Characteristics of Diesel Spray with Unsteady and Higher Injection Pressure Using a Rapid Compression Machine,” *SAE Pap. No. 910226*, 1991.

[46] A. Khalid and B. Manshoor, “Analysis of Mixture formation and Flame Development of Diesel Combustion using a Rapid Compression Machine and Optical Visualization Technique,” vol. 315, pp. 293–298, 2013.

[47] S. Shundoh, T. Kakegawa, K. Tsujimura, and S. Kobayashi, “A Study of Direct Injection Diesel Engine with 150 MPa Injection Pressure,” *Int. Symp. Comodia*, pp. 607–612, 1990.

[48] S. K. Singal and B. P. Pundir, “Fuel Spray-Air Motion Interaction in DI Diesel Engines : A Review,” *SAE Pap. No. 930604*, 1993.

[49] S. Vranckx, C. Lee, H. K. Chakravarty, and R. X. Fernandes, “A rapid compression machine study of the low temperature combustion of cyclohexane at elevated pressures,” *Proc. Combust. Inst.*, vol. 34, no. 1, pp. 377–384, 2013.

[50] K. Miwa, T. Ohmija, and T. Nishitani, “A Study of the Ignition Delay of Diesel Fuel Spray Using a Rapid Compression Machine,” *JSME Int J, Ser II*, vol. 31, p. 166, 1988.

[51] B. Kegl, “Influence of biodiesel on engine combustion and emission characteristics,” *Appl. Energy*, vol. 88, no. 5, pp. 1803–1812, May 2011.

[52] J. Arrègle, J. V Pastor, and S. Ruiz, “The Influence of Injection Parameters on Diesel Spray Characteristics,” *SAE Pap. No. 1999-01-0200*, 1999.

[53] N. A. Henein, A. Bhattacharyya, J. Schipper, and A. Kastury, “Effect of Injection Pressure and Swirl Motion on Diesel Engine-out Emissions in Conventional and Advanced Combustion Regimes,” *SAE Pap. 2006-01-0076*, vol. 2006, no. 724, 2006.

[54] M. M. Roy and H. Tsunemoto, “Effect of Injection Pressure and Split Injection on Exhaust Odor and Engine Noise in DI Diesel Engines,” *SAE Pap. No. 2002-01-2874*, 2002.

[55] C. M. Allen, E. Toulson, D. L. S. Hung, H. Schock, D. Miller, and T. Lee,

"Ignition characteristics of diesel and canola biodiesel sprays in the low-temperature combustion regime," *Energy and Fuels*, vol. 25, no. 7, pp. 2896–2908, 2011.

[56] E. Goering, W. Schwab, J. Daugherty, H. Pryde, and J. Heakin, "Fuel properties of eleven vegetable oils.," *Trans ASAE 1982*, vol. 25, pp. 1472–83, 1982.

[57] C. Zhang, B. Li, F. Rao, P. Li, and X. Li, "A shock tube study of the autoignition characteristics of RP-3 jet fuel," *Proc. Combust. Inst.*, vol. 35, no. 3, pp. 3151–3158, 2015.

[58] L. Zhong, I. P. Singh, J. Han, M. Lai, and N. A. Henein, "Effect of Cycle-to-Cycle Variation in the Injection Pressure in a Common Rail Diesel Injection System on Engine Performance," *SAE Pap. No. 2003-01-0699*, 2003.

[59] N. A. Henein, M. Lai, I. P. Singh, L. Zhong, and J. Han, "Characteristics of a Common Rail Diesel Injection System under Pilot and Post Injection Modes," *SAE Pap. No. 2002-01-0218*, 2002.

[60] S. Kobori, T. Kamimoto, and A. A. Aradi, "A Study of Ignition Delay of Diesel Fuel Sprays," *Int J Engine Res.*, vol. 1, no. 1, pp. 29–39, 1999.

[61] A. Khalid, C. Yohan, M. Jaat, I. Zaman, B. Manshoor, and M. F. M. Ali, "Effect of Preheated Fuel on Mixture Formation of Biodiesel Spray," *Appl. Mech. Mater.*, vol. 393, pp. 493–498, Sep. 2013.

[62] N. Horibe, T. Annen, Y. Miyazaki, and T. Ishiyama, "Heat Release Rate and NOx Formation Process in Two-Stage Injection Diesel PCCI Combustion in a Constant-Volume Vessel," *SAE Pap. No 2010-01-0608*, Apr. 2010.

[63] H. Ogawa, T. Li, and N. Miyamoto, "Dependence of Ultra-High EGR and Low Temperature Diesel Combustion on Fuel Injection Conditions and Compression Ratio," *SAE Pap. No 2006-01-3386*, 2006.

[64] N. Horibe, K. Takahashi, S. Kee, T. Ishiyama, and M. Shioji, "The Effects of Injection Conditions and Combustion Chamber Geometry on Performance and Emissions of DI-PCCI Operation in a Diesel Engine," *SAE Pap. No 2007-01-1874*, Jul. 2007.

[65] E. N. Balles and J. B. Heywood, "Fuel-Air Mixing and Diesel Combustion in a Rapid Compression Machine," *SAE Pap. No 880206*, 1988.

[66] C. M. Allen, E. Toulson, D. L. S. Hung, H. Schock, D. Miller, and T. Lee, "Ignition characteristics of diesel and canola biodiesel sprays in the low-temperature combustion regime," *Energy and Fuels*, vol. 25, no. 7, pp. 2896–

2908, 2011.

[67] G. E. Riva, A. Reggiori, and G. Daminelli, "Diesel Spray Combustion Rate Enhancement by Increasing Injection Pressure," *SAE Pap. No. 930926*, 1993.

[68] S.-S. Kee, A. Mohammadi, H. Hirano, Y. Kidoguchi, and K. Miwa, "Experimental study on combustion characteristics and emissions reduction of emulsified fuels in diesel combustion using a rapid compression machine," *SAE Pap. No. 2003-01-1792*, 2003.

[69] V. Schwarz, G. König, P. Dittrich, K. Binder, and D. Ag, "Analysis of Mixture Formation , Combustion and Pollutant Formation in HD Diesel Engines using Modern Optical Diagnostics and Numerical Simulation," *SAE Pap. No 1999-01-3647*, 1999.

[70] J. E. Dec and R. E. Canaan, "PLIF Imaging of NO Formation in a DI Diesel Engine," *SAE Pap. No. 980147*, 1998.

[71] T. Kamimoto and M. Bae, "High Combustion Temperature for the Reduction of Particulate in Diesel Engines," *SAE Pap. No 880423*, 1988.

[72] P. M. Najt and D. E. Foster, "Compression Ignition Homogeneous Charge Combustion," *SAE Pap. No 830264*, 1983.

[73] D. H. Qi, B. Chen, D. Zhang, and C. F. Lee, "Optical study on the combustion characteristics and soot emissions of diesel–soybean biodiesel–butanol blends in a constant volume chamber," *J. Energy Inst.*, vol. 89, pp. 807–820, 2016.

[74] Y. Wu, R. Huang, M. Leick, and C. F. Lee, "Effect of Ambient Temperature on Flame Lift-off and Soot Formation of Biodiesel Sprays," *SAE Pap. No. 2010-01-0606*, 2010.

[75] J. B. Heywood, *Internal Combustion Engine Fundamentals*. Singapore: McGraw-Hill Book Company, 1988.

[76] N. Shimazaki, H. Hatanaka, and K. Yokota, "A Study of Diesel Combustion Process Under the Condition of EGR and High-Pressure Fuel Injection with Gas Sampling Method," *SAE Pap. No. 960030*, 1996.

[77] A. Khalid and B. Manshoor, "Effect of High Injection Pressure on Mixture Formation, Burning Process and Combustion Characteristics in Diesel Combustion," *World Acad. Sci. Eng. Technol.*, vol. 71, pp. 74–77, 2012.

[78] S. H. Park, S. H. Yoon, and C. S. Lee, "Effects of multiple-injection strategies on overall spray behavior, combustion, and emissions reduction characteristics of biodiesel fuel," *Appl. Energy*, vol. 88, no. 1, pp. 88–98, Jan. 2011.

[79] M. Woods, R. Kamo, and U. S. A. Tacom, "High Pressure Fuel Injection for High Power Density Diesel Engines," *SAE Pap. No 2000-01-1186*, no. 724, 2000.

[80] H. Yamashita, T. Suzuki, H. Matsuoka, M. Mashida, and K. Kitano, "Research of the DI Diesel Spray Characteristics at High Temperature and High Pressure Ambient," *SAE Pap. No 2007-01-0665*, 2007.

[81] D. . Siebers and L. M. Pickett, "Injection Pressure and Orifice Diameter Effects on Soot in DI Diesel Fuel Jets," *Conf. Thermo Fluid Dymnamics Process.*, 2002.

[82] N. Katsura, M. Saito, J. Senda, and H. Fujimoto, "Characteristics of a Diesel Impinging on a Flat Wall," *SAE Pap. 890264*, 1989.

[83] L. M. Pickett and D. L. Siebers, "Fuel Effects on Soot Processes of Fuel Jets at DI Diesel Conditions Reprinted From : Experimental Investigation of Compression Ignition and," *SAE Pap. No. 2003-01-3080*, 2003.

[84] Y. Sato and A. Noda, "Effects of Fuel Injection Characteristics on Heat Release and Emissions in a DI Diesel Engine Operated on DME," *SAE Pap. No. 2001-01-3634*, 2001.

[85] O. Abiola, J. Zhu, K. Nishida, X. Wang, and Z. Huang, "Characterization of spray and combustion processes of biodiesel fuel injected by diesel engine common rail system," *Fuel*, vol. 104, pp. 838–846, 2013.

[86] L. Ranganathan and S. Sampath, "A review on biodiesel production , combustion , emissions and performance," *Int. J. Adv. Sci. Tech. Res.*, vol. 1, no. 1, pp. 86–106, 2011.

[87] J. Porteiro, E. Granada, and J. C. Mora, "Performance and exhaust emissions in the use of biodiesel in outboard diesel engines," vol. 86, pp. 1765–1771, 2007.

[88] Y. Devarajan, A. M. Dinesh Babu Munuswamy, and B. Nagappan, "Performance , combustion and emission analysis of neat palm oil bio-diesel and higher alcohol blends in diesel engine," *Energy Fuel*, 2017.

[89] I. Mahmud and H. M. Cho, "A review on characteristics , advantages and limitations of palm oil biofuel," *Int. J. Glob. Warm.*, vol. 14, no. 1, pp. 81–96, 2018.

[90] E. Öztürk, "Performance, emissions, combustion and injection characteristics of a diesel engine fuelled with canola oil–hazelnut soapstock biodiesel mixture," *Fuel Process. Technol.*, vol. 129, pp. 183–191, 2015.

[91] D. H. Qi, H. Chen, L. M. Geng, and Y. Z. H. Bian, "Experimental studies on

the combustion characteristics and performance of a direct injection engine fueled with biodiesel / diesel blends," vol. 51, pp. 2985–2992, 2010.

[92] L. Labecki and L. C. Ganippa, "Effects of injection parameters and EGR on combustion and emission characteristics of rapeseed oil and its blends in diesel engines," *Fuel*, vol. 98, pp. 15–28, 2012.

[93] M. S. Graboski and R. L. McCormick, "Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines," *Prog. Energy Combust. Sci.*, vol. 24 (2), pp. 125–164, 1998.

[94] M. P. B. Musculus and P. Mark, "On the Correlation between NOx Emissions and the Diesel Premixed Burn," *SAE Pap. 2004-01-1401*, 2004.

[95] S. Lahane and K. A. Subramanian, "Effect of different percentages of biodiesel–diesel blends on injection, spray, combustion, performance, and emission characteristics of a diesel engine," *Fuel*, vol. 139, pp. 537–545, 2015.

[96] A. N. Ozsezen and M. Canakci, "Determination of performance and combustion characteristics of a diesel engine fueled with canola and waste palm oil methyl esters," *Energy Convers. Manag.*, vol. 52, no. 1, pp. 108–116, 2011.

[97] Y. Liu, J. Li, and C. Jin, "Fuel spray and combustion characteristics of butanol blends in a constant volume combustion chamber," *Energy Convers. Manag.*, vol. 105, pp. 1059–1069, 2015.

[98] Y. Wu, R. Huang, M. Leick, and C. F. Lee, "Effect of Ambient Temperature on Flame Lift-off and Soot Formation of Biodiesel Sprays," *SAE 2010-01-0606*, 2010.

[99] A. Khalid, K. Hayashi, Y. Kidoguchi, and T. Yatsufusa, "Effect of Air Entrainment and Oxygen Concentration on Endothermic and Heat Recovery Process of Diesel Ignition," *SAE Tech. Pap.*, pp. 1–5, 2011.

[100] O. M. Ali, R. Mamat, N. R. Abdullah, and A. Adam, "Analysis of blended fuel properties and engine performance with palm biodiesel e diesel blended fuel," *Renew. Energy*, vol. 86, pp. 59–67, 2016.

[101] N. Jaat, A. Khalid, A. Sapit, A. Rhaodah, M. Basharie, and M. Fawzi, "The influences of injection pressure and ambient temperature on ignition delay and emission," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 12, pp. 7522–7528, 2016.

[102] K. Ryu, "Effects of pilot injection timing on the combustion and emissions characteristics in a diesel engine using biodiesel – CNG dual fuel," *Appl. Energy*, vol. 111, pp. 721–730, 2013.

[103] Abd Fathul Hakim bin Zulkifli, "Diesel-CNG Fuel Combustion Characterization Using Vibro-Acoustic Analysis and Response Surface Methodology," Universiti Tun Hussein Onn Malaysia, 2019.

[104] T. C. Zannis, D. T. Hountalas, and D. A. Kouremenos, "Experimental Investigation to Specify the Effect of Oxygenated Additive Content and Type on DI Diesel Engine Performance and Emissions," *SAE 2004-01-0097*, 2004.

[105] R. P. Rodríguez, R. Sierens, and S. Verhelst, "Ignition delay in a palm oil and rapeseed oil biodiesel fuelled engine and predictive correlations for the ignition delay period," *Fuel*, vol. 90, no. 2, pp. 766–772, 2011.

[106] A. A. Yu CW, Bari S, "A comparison of combustion characteristics of waste cooking oil with diesel as fuel in a direct injection diesel engine.," *Proc IMechE Part D J Automob. Eng*, no. 216, pp. 237–43, 2002.

[107] D. L. Sahoo PK, "Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine.," *Fuel*, vol. 88, pp. 994–9, 2009.

[108] A. K. Agarwal and L. M. Das, "Biodiesel development and characterization for use as a fuel in compression ignition engines.," *Trans ASME*, vol. 132, pp. 440–7, 2001.