EFFECT OF HIGH INJECTION PRESSURE AND AMBIENT TEMPERATURE ON HEAT RELEASE IN BIODIESEL COMBUSTION

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A thesis submitted in
Fulfillment of the requirement for the award of the
Degree of Master of Mechanical Engineering

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ACKNOWLEDGEMENT

The author would like to express grateful to the Allah for the good health and well being that were necessary to complete this thesis. The author also wish to express my sincere thanks to Associate Professor Dr. Amir Bin Khalid my supervisor for providing me with all the sincere and valuable guidance and encouragement extended to me. I am also grateful to My PhD Research partner Mr Md Norrizam Bin Mohmad Jaat and Dr. Mas Fawzi Bin Mohd Ali extremely thankful and indebted to them for sharing expertise and knowledge. The author to take this opportunity to express gratitude to all of the faculty members for their help and support. The author also thank to my parents and families for the unceasing encouragement, support and attention. I also place on record, my sense of gratitude to one and all, who directly or indirectly, have lent their hand in this venture. Finally, the author wish to thank the financial support of the Development of Single-shot Common-rail for Biodiesel Combustion Co-E MTUN-C009 grant that funded this project.
ABSTRACT

Biodiesel remains an alternative fuel of interest for use in diesel engines because biodiesel fuel is economic, low density and has low viscosity. However, biodiesel fuel contributes to the exhaust emissions in term of particulate matter (PM) and nitrogen oxides (NOx). To solve this problem, a high injection pressure and ambient temperature were suggested. These factors are key elements during the ignition delay and burning process that highly affect the exhaust emissions such as Particulate Matter (PM) and Nitrogen Oxide (NOx) during the combustion process. The reduction of emissions can be achieved through the improvement in mixing fuel and air especially during the ignition delay period. The purpose of this study is to clarify the effect of variant ambient temperature and high injection pressure on combustion process and heat release using biodiesel fuel. Measurements were made in piezoelectric pressure transducer sensor on rapid compression machine (RCM) which intended to simulate the actual compression period related phenomena. The RCM has established that with high repeatable experiment condition, up to 5 MPa and greater than 1000 K can be obtained. The biodiesel or diesel combustion was simulated using the RCM which is equipped with Denso- single-shot common-rail fuel injection system which is capable of a maximum injection pressure up to 140 MPa. The fuels that were used in this experiment are standard diesel, B5, B10 and B15. The results show that high injection pressure and variant ambient temperature using biodiesels fuel for B5, B10 and B15 strongly affects the atomization, endothermic, fuel evaporation rates during ignition delay and also affect exothermic and heat release during the combustion process. During high ambient temperature for $T_i= 900$ K, the period of ignition delay is become short less than 0.5 ms, the combustion become peak it almost 9 MPa and the duration of heat release is decreased around 6 ms. However, for high injection pressure at $P_{inj}= 140$ MPa the duration of ignition delay is more than 0.5 ms, but the duration of heat release is
reduction around 5 ms. When biodiesel fuel (B5, B10 and B15) used, the ignition delay is become longer more than 0.5 ms and the duration of heat release is also longer more than 6 ms.
ABSTRAK

Bahan api biodiesel masih mendapatpermintaan sebagai bahan api alternatif yang digunakan dalam enjin diesel kerana bahan api biodieseljimut, ketupatan yang rendah dan kelikan yang rendah. Walau bagaimanapun, bahan api biodiesel menyumbang kepada pelepasan ekzos dari segi Particulate Matter (PM) dan Nitrogen Oxide (NOx). Untuk menyelesaikan masalah ini, tekanan suntikan yang tinggi dan berbeza-beza suhu persekitaran telah dicadangkan. Faktor-faktor ini merupakan elemen utama dalam pencucuhan lengah dan proses pembakaran yang menyumbang kepada pelepasan ekzos seperti particulate matter (PM) dan nitrogen oxides (NOx) ketika proses pembakaran. Pengurangan pelepasan boleh dicapai melalui peningkatan percampuran bahan api dan udara terutamanya dalam pencucuhan lengah. Tujuan kajian ini adalah untuk mengenalpasti kesan suntikan tekanan tinggi dan berbeza-bezasuhi persekitaran ke atas campuran dan proses pembakaran bahan api biodiesel. Pengukuran telah dibuat dalam piezoelektrik sensor tekanan transducer pada mampatan mesin pesat (RCM) yang bertujuan untuk mensimulasikan fenomena tempoh mampatan sebenar yang berkaitan. RCM ini membuktikan bahawa pengujian yang berulang dapat menghasilkan tekanan sehingga 5 MPa dan suhu melebihi 1000 K. Simulasi pembakaran diesel menggunakan RCM yang dilengkapi dengan sistem common-rail suntikan bahan apiDenso suntikan tunggal yang mampu mengawal tekanan suntikan maksimum sehingga 140 Mpa. Bahan api suntikan yang digunakan di dalam ujikaji ini adalahdiesel standard, B5, B10 dan B15. Keputusan menunjukkan tekanan suntikan dan berbeza-beza suhu persekiataranyang menggunakan pelbagai bahan api biodiesel memberi kesan yang ketara ke atas pembentukan campuran, endotermik, kadar penyelatan bahan api semasa pencucuhan lengah dan juga memberi kesan ke atas eksotermik, pembebasan haba semasa proses pembakaran. Semasa suhu ambien yang tinggi untuk Ti = 900 K, tempoh kelewatuan pencucuhan adalah menjadi pendek kurang daripada 0.5 ms, pembakaran menjadi puncak hampir 9 MPa dan tempoh pembebasan haba dikuangkan sekitar 6 ms. Walau bagaimanapun, bagi suntikan tekanan tinggi pada P_{inj} = 140 MPa tempoh
lengah adalah lebih daripada 0.5 ms, tetapi tempoh pembebasan haba adalah
berkurang sekitar 5 ms. Apabila bahan api biodiesel (B5, B10 dan B15) yang
digunakan, kelewat penting menjadi lebih lama lebih daripada 0.5 ms dan
tempoh pelepasan haba adalah juga lebih panjang lebih daripada 6 ms.
TABLE OF CONTENTS

TITLE
DECLARATION
ACKNOWLEDGEMENT
ABSTRACT
ABSTRAK
TABLE OF CONTENTS
LIST OF TABLES
LIST OF FIGURES
LIST OF SYMBOLS AND ABBREVIATIONS
LIST OF APPENDICES

1.0 INTRODUCTION
1.1 Background of research
1.2 Problem statement
1.3 Objective of study
1.4 Scopes of study
1.5 Thesis Outline

2.0 LITERATURE VIEW
2.1 Introduction
2.2 Biodiesel Renewable Resource
   2.2.1 Biodiesel Properties
2.3 Conventional and Modern Concept of Diesel Combustion
   2.3.1 Definition of Ignition Delay
   2.3.2 Effect of Injection Pressure and Ambient Temperature on Ignition Delay
2.4 Concept Review of Existing Rapid Compression
Machine (RCM) 25
2.4.1 Compression Process 31
2.5 Principle Working of Common Rail System 34
2.6 Determination of Heat Release Rate during Combustion 36
2.6.1 Effect of Biodiesel Fuel on Heat Release 37
2.6.2 Influence of High Injection Pressure and Ambient Temperature on Heat Release 38
2.6.3 Combustion Process in Diesel Combustion 40
2.6.4 Effect of Biodiesel on Air Pollution 41
2.7 Summary of literature reviews 42

3.0 METHODOLOGY 43
3.1 Introduction 43
3.2 Development of Rapid Compression Machine (RCM) 45
3.3 Apparatus Setup 46
3.3.1 Schematic of Apparatus Setup 46
3.3.2 Rapid Compression Machine (RCM) 47
3.3.3 Common Rail System Setup 49
3.3.4 Injector Type 52
3.3.5 Fuel Quantity 53
3.4 Controller and Data Acquisition Systems 55
3.5 Premixed Combustion 58
3.6 Fuel Type 60
3.6.1 Biodiesel Production 61
3.6.2 Calculation of Biodiesel Blended Fuel 62
3.6.3 Blended Biodiesel 63
3.7 General Procedures 64
3.8 Summary of Research Methodology 65

4.0 RESULTS AND DISCUSSION 66
4.1 Introduction 66
4.2 Effect of Design Parameter of injection, Temperature
and biodiesel on Mixture Formation and Combustion Process

4.2.1 Effects of Ambient Temperature on Ignition Delay and Combustion Process 67

4.2.2 Effect of Injection Pressure on Ignition Delay and Combustion Process 71

4.2.3 Effect of Fuel Biodiesel Blended on Ignition Delay and Combustion Process 74

4.3 Effect of Ambient Temperature, Injection Pressure and Biodiesel Blended on Heat Release 76

4.4 Effects of Initial Temperature on ignition, Flame Development and Heat Release 81

4.5 Influence of Ambient temperature on Emission 83

4.6 Summary of Result and Discussion 86

5.0 CONCLUSION AND RECOMMENDATION 87

5.1 Conclusion 87

5.2 Recommendation 88

REFERENCES 90

APPENDICES 99
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Comparison of density and kinematic viscosity for various types of biodiesel</td>
<td>15</td>
</tr>
<tr>
<td>2.2 Different standards and specifications for palm biodiesel</td>
<td>15</td>
</tr>
<tr>
<td>2.3 Review of existing of RCM</td>
<td>27</td>
</tr>
<tr>
<td>3.1 Experiment Parameters</td>
<td>49</td>
</tr>
<tr>
<td>3.2 Test Bench Specification</td>
<td>50</td>
</tr>
<tr>
<td>3.3 Specification of Injector Denso</td>
<td>52</td>
</tr>
<tr>
<td>3.4 Quantity of Denso injector</td>
<td>54</td>
</tr>
<tr>
<td>3.5 Fuel properties based on ASTM</td>
<td>61</td>
</tr>
<tr>
<td>3.6 Fuel Properties</td>
<td>62</td>
</tr>
<tr>
<td>3.6 Biodiesel formulae</td>
<td>63</td>
</tr>
<tr>
<td>4.1 Experimental parameters (Variant ambient temperature)</td>
<td>68</td>
</tr>
<tr>
<td>4.2 Experimental parameters (Variant injection pressure)</td>
<td>72</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Europe diesel cars sale</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>The diesel engine technologies for CO₂ reductions</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>The greenhouse gas by sector</td>
<td>6</td>
</tr>
<tr>
<td>1.4</td>
<td>Comparison of worldwide fuel economy, fuel consumption, or proposed CO₂ standards</td>
<td>6</td>
</tr>
<tr>
<td>1.5</td>
<td>General comparison of on-road Heavy Duty Diesel (HDD) Standards for truck emission regulation</td>
<td>7</td>
</tr>
<tr>
<td>1.6</td>
<td>Summary of United States EPA evaluation of biodiesel impact on pollutant</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Density, kinematic viscosity vs biodiesel ratio for RBDPO, soy methyl, and palm oil</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Phases of the conventional diesel combustion process</td>
<td>18</td>
</tr>
<tr>
<td>2.3</td>
<td>Extended view of ignition delay</td>
<td>20</td>
</tr>
<tr>
<td>2.4</td>
<td>Time history of pressure in combustion chamber</td>
<td>21</td>
</tr>
<tr>
<td>2.5</td>
<td>Comparison of ignition delay with different injection pressures, injection timings and engine loads: (a) low load, (b) high load condition</td>
<td>23</td>
</tr>
<tr>
<td>2.6</td>
<td>Temporal variation in model predicted ambient temperature</td>
<td>24</td>
</tr>
<tr>
<td>2.7</td>
<td>Model of RCM for diesel combustion</td>
<td>28</td>
</tr>
<tr>
<td>2.8</td>
<td>Schematic of Model of RCM</td>
<td>29</td>
</tr>
<tr>
<td>2.9</td>
<td>Schematic of combustion chamber</td>
<td>31</td>
</tr>
<tr>
<td>2.10</td>
<td>Pressure and temperature during premixed combustion</td>
<td>32</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>2.11</td>
<td>Pressure and temperature during premixed combustion</td>
<td>33</td>
</tr>
<tr>
<td>2.12</td>
<td>Pressure traces measured in RCM for inert-gas mixtures for various pressures</td>
<td>34</td>
</tr>
<tr>
<td>2.13</td>
<td>Schematic diagram of common rail</td>
<td>35</td>
</tr>
<tr>
<td>2.14</td>
<td>Variation of heat release rate for biodiesel fuel blends</td>
<td>37</td>
</tr>
<tr>
<td>2.15</td>
<td>Comparison of in-cylinder pressure and heat release rate with different injection pressures and engine loads: (a) low load, (b) high load condition</td>
<td>39</td>
</tr>
<tr>
<td>2.16</td>
<td>Effect of injection pressure and swirl velocity on flames</td>
<td>41</td>
</tr>
<tr>
<td>2.17</td>
<td>Effect of injection pressure on projected flame area</td>
<td>41</td>
</tr>
<tr>
<td>3.1</td>
<td>Flow chart of research project</td>
<td>44</td>
</tr>
<tr>
<td>3.2</td>
<td>The general schematic diagram of RCM</td>
<td>46</td>
</tr>
<tr>
<td>3.3</td>
<td>Condition of piston before and after experiment</td>
<td>48</td>
</tr>
<tr>
<td>3.4</td>
<td>Combustion Chamber</td>
<td>48</td>
</tr>
<tr>
<td>3.5</td>
<td>Common rail injection system</td>
<td>50</td>
</tr>
<tr>
<td>3.6</td>
<td>Schematic diagram of Common Rail System</td>
<td>51</td>
</tr>
<tr>
<td>3.7</td>
<td>Schematic diagram of injector build up and nozzle injector</td>
<td>53</td>
</tr>
<tr>
<td>3.8</td>
<td>Effect of pressure injector to fuel quantity</td>
<td>54</td>
</tr>
<tr>
<td>3.9</td>
<td>Flow of data measurement</td>
<td>56</td>
</tr>
<tr>
<td>3.10</td>
<td>Sample of graph combustion process</td>
<td>57</td>
</tr>
<tr>
<td>3.11</td>
<td>Sample of (a) combustion process and (b) heat release after calculation</td>
<td>58</td>
</tr>
<tr>
<td>3.12</td>
<td>Effect of initial temperature on pressure history</td>
<td>59</td>
</tr>
<tr>
<td>3.13</td>
<td>Effect of initial temperature on temperature histories</td>
<td>60</td>
</tr>
<tr>
<td>3.14</td>
<td>Schematics of biodiesel blending machine</td>
<td>64</td>
</tr>
<tr>
<td>4.1</td>
<td>Effect of ambient temperature on ignition delay</td>
<td>70</td>
</tr>
<tr>
<td>4.2</td>
<td>Influence of ambient temperature on combustion</td>
<td>71</td>
</tr>
<tr>
<td>4.3</td>
<td>Effect of injection pressure on ignition delay.</td>
<td>73</td>
</tr>
<tr>
<td>4.4</td>
<td>Effect of high injection pressure on combustion process</td>
<td>74</td>
</tr>
<tr>
<td>4.5</td>
<td>Influence of biodiesel on ignition delay</td>
<td>75</td>
</tr>
<tr>
<td>4.6</td>
<td>Comparison of biodiesel on combustion process</td>
<td>76</td>
</tr>
</tbody>
</table>
4.7 Influence of ambient temperature on heat release 77
4.8 Effect of ambient temperature on combustion Characteristics 78
4.9 Effect of high injection pressure on heat release 79
4.10 Influence of injection pressure on combustion Characteristic 80
4.11 Effect of biodiesel on heat release 81
4.12 Effect of initial temperature on combustion and heat release 83
4.13 Effect of ambient temperature on emission 85
# LIST OF SYMBOLS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
</tr>
<tr>
<td>ACEA</td>
<td>European Automobile Manufacturers Association</td>
</tr>
<tr>
<td>AECC</td>
<td>Association for Emissions Control by Catalyst</td>
</tr>
<tr>
<td>AF</td>
<td>Air-fuel ratio</td>
</tr>
<tr>
<td>Ar</td>
<td>Argon</td>
</tr>
<tr>
<td>BDF</td>
<td>Bio-Diesel Fuel</td>
</tr>
<tr>
<td>B5</td>
<td>5% Biodiesel</td>
</tr>
<tr>
<td>B10</td>
<td>10% Biodiesel</td>
</tr>
<tr>
<td>B15</td>
<td>15% Biodiesel</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>°C</td>
<td>Celsius</td>
</tr>
<tr>
<td>CI</td>
<td>Compression Ignition</td>
</tr>
<tr>
<td>CPO</td>
<td>Crude Palm Oil</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DI</td>
<td>Direct Injection</td>
</tr>
<tr>
<td>dQ/dt</td>
<td>Heat Release Rate</td>
</tr>
<tr>
<td>EDU</td>
<td>Electronic Drive Unit</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ESC</td>
<td>European Steady-state Cycles</td>
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<tr>
<td>ETC</td>
<td>European Transient-state Cycles</td>
</tr>
<tr>
<td>EU</td>
<td>Europe United</td>
</tr>
<tr>
<td>FA</td>
<td>Fuel-Air ratio</td>
</tr>
<tr>
<td>GOME</td>
<td>Grapeseed Oil Methyl Ester</td>
</tr>
</tbody>
</table>
SO - Soybean Oil
H₂ - Hydrogen
HC - Hydrocarbon
H₂O - Water
HDD - Heavy-duty diesel
HR - Heat Release
HRR - Heat Release Rate
ICCT - International Council for Clean Transportation
K - Kelvin
kPa - Kilopascal
MPa - Megapascal
ms - Millisecond
MWₐ - Air molecular weight
MWᵢ - Diesel molecular weight
MWₖ - Water molecular weight
NEDC - New European Drive Cycle
N₂ - Nitrogen
NOₓ - Nitrogen Oxides
O₂ - Oxygen
O₃ - Ozone
P - Pressure
pₑ - Pressure Chamber
p₀ - Ambient Pressure
pᵣ - Fired cycle pressure
pₑ - non-injection pressure
Pᵢₙj - Fuel injection Pressure
PM - Particulate matter
PO - Palm Oil
POME - Palm Oil Methyl Ester
PRR - Pressure Rise Rate
RBDPO - Refined, Bleached and Deodorized Palm Oil
q_i \quad - \quad \text{Quantity fuel injection}

RCM \quad - \quad \text{Rapid Compression Machine}

r_s \quad - \quad \text{Swirl velocity}

SO_2 \quad - \quad \text{Sulfur Dioxide}

SOI \quad - \quad \text{Start of Ignition}

T \quad - \quad \text{Temperature}

T_i \quad - \quad \text{Initial Temperature}

T_a \quad - \quad \text{Ambient Temperature}

T_s \quad - \quad \text{Surface Temperature}

t \quad - \quad \text{time}

\text{t}_{\text{inj}} \quad - \quad \text{time injection}

TDC \quad - \quad \text{Top Dead Center}

v \quad - \quad \text{Velocity}

\text{vol}\% \quad - \quad \text{Volume Gas Concentration}

US \quad - \quad \text{United State}

USEPA \quad - \quad \text{United States Environmental Protection Agency}

WCO \quad - \quad \text{Waste Cooking Oil}

\Phi \quad - \quad \text{Equivalent ratio}

\rho \quad - \quad \text{Density}

m \quad - \quad \text{Mass flow rate}

m_a \quad - \quad \text{Air flow rate}

m_f \quad - \quad \text{Fuel flow rate}

\text{(FA)}_{\text{act}} \quad - \quad \text{Actual fuel-air ratio}

\text{(FA)}_{\text{stoich}} \quad - \quad \text{Stoichiometric fuel-air ratio}

\text{(AF)}_{\text{act}} \quad - \quad \text{Actual air-fuel ratio}

\text{(AF)}_{\text{stoich}} \quad - \quad \text{Stoichiometric air-fuel ratio}
<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sample of calculation</td>
<td>99</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Research Background

Internal combustion engine is by far the most important power train for various types of vehicles, involving on-road and off-road applications, such as passenger cars, trucks, heavy construction, agriculture vehicles, locomotives and ships. Internal combustion engine dates back to 1892 with the patent of the basic concept in diesel engine technologies by a German engineer, Rudolf Diesel (1858-1913).

The main objective of internal combustion engine is to produce mechanical power from fuel, in terms of its chemical energy contents. In recent years, development of diesel engines ranges from small to large size designs which contributed to an increase in engine efficiency significantly, especially in heavy industrial diesel engines. This led to a more restrictions imposed for all diesel engines specification, namely the exhaust gas limit, power output, fuel consumption, noise, cost, as well as high demand on drive ability and its diagnosis[1]-[3].

Figure 1.1 shows the trend in the sale of diesel cars in Europe which is constantly increasing throughout the years. This proves that the interest in diesel cars in Europe is high, since the first time it was introduced in the market. The diesel engine popularity as oppose to other internal combustion engines is largely influenced by its engine efficiency and excellent durability, thus results to better fuel economy and fuel consumption. Nevertheless, fuel efficiency is the key purchase requirement which has influenced majority of vehicles consumers, as their main preference criteria [4].
Diesel combustion process is a series of event starting a moment when fuel is injected into hot ambient temperature inside combustion which include fuel droplet, atomizes (atomization process), vaporization process, combustible ready mixture, ignition delay combustion. The combustion process is initiated by auto-ignition. However, during the combustion process, the diesel engine generates undesirable emission, contributes as one of the major sources of pollution which is hydrocarbon; in particularly –carbon dioxide (CO₂), carbon monoxide (CO), nitrogen monoxide (NO), nitrogen oxides (NOₓ) and particulate matter (PM).

For this reason partly due to environmental awareness and concern, many researches were developed to optimize diesel engines so that it will emit a low level of exhaust emission especially CO₂ and at the same time, avoiding decrease in performance and efficiency. Figure 1.2 depicts an analysis of advancement in diesel technologies for CO₂ reduction. From the figure, it can be seen that for an average sized European car (1400 kg), the 2020 CO₂ target value of 95 g/km is nearly achieved for diesel without
hybridization. Thus for this reason, novel technologies for diesel engine need to be utilized, such as improving power of turbo-charging, higher injection pressures from common-rail injection, higher peak cylinder pressure, variable valve technology, and more charge air cooling [5].

![Diesel technologies for CO2 reductions](image)

**Figure 1.2:** The diesel engine technologies for CO2 reductions [5]

During combustion process the compression ignition is occurring, there are some regions where partially oxidized hydrocarbon (HC) and carbon monoxide (CO) will be created in incomplete combustion. This is because of fuel-rich regions not completely burning during combustion as insufficient oxygen will be available to fuel pyrolysis and facilitate combustion can occur. There are many species of unburned hydrocarbons formed during combustion process, including: semi-volatile organic compounds, volatile organic gases, and particle phase organic compounds [6]. The environment and health impacts from hydrocarbon (HC), certain hydrocarbon species such as poly aromatic hydrocarbons are recognized to be known human carcinogens. Meanwhile, for carbon monoxide effect to environment and health impacts, CO is a colourless and odorless gas,
and has been related to pathological and physiological changes within the human body potentially causing death at high exposures. Acute CO exposure has also been shown to produce myocardial and neurological injury.

For nitrogen oxides, $\text{NO}_x$ (NO+NO$_2$) emission from diesel engine, NO$_x$ is formed through some mechanism: fuel NO$_x$, thermal NO$_x$ (Zeldovich mechanism) and prompt NO$_x$ (Fenimore mechanism). Fuel NO$_x$ simply involves the formation of NO$_x$ from fuel bound nitrogen; although fuel bound nitrogen is typically not found in diesel fuels [7]. However for thermal NO$_x$, the formation of NO is created mixture between nitrogen and oxygen gas, as given by the following reaction:

$$\frac{1}{2} \text{N}_2 + \frac{1}{2} \text{O}_2 = \text{NO}$$  \hspace{1cm} (1)

The Zeldovich mechanism can be mostly describe by three reaction, as given by the following reaction:

$$\text{O} + \text{N}_2 \leftrightarrow \text{NO} + \text{N} \hspace{1cm} (2)$$
$$\text{N} + \text{O}_2 \leftrightarrow \text{NO} + \text{O} \hspace{1cm} (3)$$
$$\text{N} + \text{OH} \leftrightarrow \text{NO} + \text{H} \hspace{1cm} (4)$$

The Zeldovich mechanism is almost called thermal NO$_x$ because it is sensitive to temperature, due to the very high activation energy required for equation 2 to proceed [7]. However, effect of environment health from NO$_x$, NO$_x$ contributes to a wide range of environmental effects including the creation of acid rain, Particulate Matter PM$_{2.5}$ (via formation of secondary particulates such as ammonium nitrate) with resulting health impacts and contributions to regional haze, eutrophication of aquatic ecosystems (via addition of excess nitrogen), and elevated ozone ($\text{O}_3$) concentrations (via reaction with hydrocarbons and carbon monoxide) with resulting impacts on health and environment [8].

The another emission that effected on environment and health is particulate matter (PM), PM is composed of agglomerated solid carbonaceous material, organic compounds, sulfur compounds, and trace elements. Over the decades, there has been a significant low in the PM mass concentration exhausted from diesel engines, due to
improved engine design. The impacts of particulate matter in environment and health, being a complex mixture of soot, sulphates, metals, and ash, has been related to higher incidence rates of cancer, respiratory diseases and symptoms. Diesel particulate matter has also been recognized by the United States Environmental Protection Agency (USEPA) as a likely human carcinogen [9].

Because of this reason in term of emission and environment and health impacts, the greenhouse gases were proposed, the figure 1.3 shows the amount of greenhouse gases emitted to the atmosphere due to the effect of compression-ignition engines or diesel combustion engines on global systems. The emission contribution of greenhouse gases is seen to be led by the electricity sector with a percentage of 33%, followed by the transportation sector at 28%, agriculture sector at 20% and the industry sector at 19%. In a more detailed analysis for the transportation sector, the passenger-car type vehicles leads the contribution of the gases with 33% which shows that it is the biggest contributor compared to light duty trucks at 29%. This fact causes greater air pollution and exhibits relatively higher concentrations of greenhouse gases in atmosphere [2].

Figure 1.4 illustrates a study conducted by the New European Drive Cycle (NEDC), in which depicts the trend in CO₂ emissions in comparison with the fuel economy (i.e. fuel consumption requirements) trend across the world. The decline trend poses an interesting observation, in which it shows although the whole technology efforts went into fuel consumption improvement; vehicle CO₂ reductions progressed approximately between 1% to 1.5% per year, led by both the United States and Europe.
Figure 1.3: The greenhouse gas by sector [2]

Figure 1.4: Comparison of worldwide fuel economy, fuel consumption, or proposed CO₂ standards [5]
However, the present challenge for diesel engines is to reduce raw emission such as Nitrogen Oxide (NO$_x$) and Particular Matter (PM) into the atmosphere, apart from the optimization in CO$_2$-reduction with maintained high fuel and power efficiencies as stated earlier, given the latter being the main advantage for preference of this engine type. Many researchers have been carried out in order to evaluate the actual emission and characteristics. The on-road Heavy-Duty Diesel (HDD) standards as shown Figure 1.5 are estimates of engine emissions performance in Japan and the US, which have already set their standard rules for the next 5 to 10 years, with the Europe following closely from behind, being just started the process. However, surveys on industry stakeholders showed that the European Commission [10] recently proposed NO$_x$ standards of 400 mg/kW-hr and PM standards of 10 mg/kW-hr; as measured on the current European Steady-state, and Transient Cycles (ESC and ETC respectively). Major stakeholders, representing the truck manufacturing industry, European Automobile Manufacturers Association (ACEA); the emissions controls industry, Association for Emissions Control by Catalyst (AECC); and the environmental community, International Council for Clean Transportation (ICCT); supported these levels, respect to the Commission’s proposal [10].

Figure 1.5: General comparison of on-road Heavy Duty Diesel (HDD) Standards for truck emission regulation [10]
One of the solutions to control these emissions from diesel engines is by using biodiesel fuel, in which Bio-Diesel Fuel (BDF) engines are still widely needed and applicable to a wide variety of applications ranging from small to large sizes. Bio-diesel is made from natural, such as new or used vegetable oils and animal fats; that provides an alternative fuel with a cleaner-burning diesel. As an example, for the petroleum diesel, bio-diesel operates in diesel engines. Malaysia has started to use diesel engines using palm oil as alternative fuel, since it is a potentially highly attractive and performs much better than other types of fuel [11]. Compared to the properties of conventional diesel, palm oil fuel is not significantly different, save that the latter has a higher specific gravity and viscosity with a slightly lower cetane index. Based on a research study, between the conventional diesel fuel and palm oil fuel, the engine performance and exhaust emissions using palm oil fuel and its blends with conventional diesel fuel in stationary diesel engines are comparable. Palm oil fuel is more environment-friendly, and the exhaust emission is much cleaner since it emits less black smoke, CO, HC, with the absence of SO₂ excluding NOₓ[12].

However, BDF diesel engines still pose a problem of emitting NOₓ and Particular Matter (PM) into the atmosphere. This is due to a few factors, namely: oxidation stability, cetane number, stoichiometric point, bio-fuel composition, and anti-oxidations on the degradation are extremely viscous. Therefore, improvement on BDF engines emission is an urgent necessity, to adhere with the expected stringent emission regulations.

Generally, BDF combustion is by nature a heterogeneous combustion. NOₓ is formed at high temperature and at the stoichiometric mixture region. PM, on the other hand, is emitted at the rich region. It is generally known that, in order to control the mixture formation, improvement on the exhaust emission from diesel engines is indispensable [13]. Figure 1.6 shows the summary of an evaluation conducted by the United States Environmental Protection Agency (EPA), in which they produced a review on a published biodiesel emission data for heavy duty engines. Based on the illustrated evaluation of the impacts of biodiesel towards pollution, comparing the
results for NO$_x$, PM, CO, and HC, the NO$_x$ emission is shown to increase by approximately 10%.

Figure 1.6: Summary of United States EPA evaluation of biodiesel impact on pollutant [13]

1.2 Problem Statements

Modern diesel engines release high nitrogen oxide (NO$_x$), as a result of diesel and biodiesel combustions, located either in the internal combustion engine, or the external burner system which will cause environmental and health hazards. When the percentage of biodiesel fuel is increased, the emitted NO$_x$ also increases, apart from lower viscosity, density, Carbon Monoxide (CO), and Hydrocarbon (HC).

Although the improvement on mixture formation and combustion characteristics of biodiesel fuel is an effective way to encounter the problem stated above, there are also implementation concerns that need to be addressed concurrently, namely:
i. The effect of ambient temperature (T) parameter on ignition delay and heat release.
ii. The effect of high injection pressure (P_{inj}) from common rail system on ignition delay during premixed combustion and heat release.

1.3 Objectives of Study

The objectives of this research are:

a) To investigate the effects of mixture formation during ignition delay in premixed combustion process and heat release using biodiesel fuel.
b) To analysis the effects of ambient temperature (T) and injection pressure (P_{inj}) on ignition delay and heat release rate during the combustion process.

1.4 Scope of Study

This research is done based on the identified scope of study as follows:

a) The fuel used is biodiesel for B5, B10, B15 and diesel standard as the baseline fuel.
b) The range of ambient temperatures are set at 700 K, 800 K and 900 K.
c) The injection pressures are set at 100 MPa, 120 MPa and 140 MPa.

1.5 Thesis Outline

This thesis consists of 5 chapters. Chapter 1 is provides an introduction to the research which includes the research background, problem statements, objectives as well as the scope of study of the conducted research. The literature review is presented in Chapter 2
and covers topics ranging from the required basic understanding in diesel combustion engines, the performances and emission characteristics and related information on engine diversification techniques. In Chapter 3, the experimental apparatus, i.e. the Rapid Compression Machine (RCM) is presented, in which it includes the injection of common-rail system, the direct photography capture method, the heater system as well as the measurement of gas analyzer employed in the research. All of the experimental results are presented and discussed, supported by respective evidences are presented in Chapter 4. In the final chapter – Chapter 5, a series of conclusions drawn from the conducted research work are presented.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a review on the current status that had been carried out on mixture formation, combustion process and heat release rate using diesel and biodiesel fuel. Diesel engines are internal combustion engines that use high compression pressure to initialize the ignition due to high temperature in the combustion chamber. It is commonly known that the diesel spray ignition is caused by the fuel-air mixture characteristic. Apart from that, the Rapid Compression Machine (RCM) is a good tool to be used to study high pressure auto-ignition of combustible mixtures. This is because the RCM provides a combustion process directly and ignition delay indirectly.

2.2 Biodiesel Renewable Resource

Fuel plays a vital role in control of performance during combustion. Currently, biodiesel fuel is one of the types of fuel that is gaining much attention, being a major crude oil in the world market demand in the automotive, light and heavy manufacturing industries; are widely used all over the world. Many researches are focused on the development on
biodiesel. This is because biodiesel is an attractive renewable resource that possesses similar characteristics to diesel.

Biodiesel derived from different plant oils contains slightly different molecular structures. This includes carbon-chain lengths, hydrogen-carbon ratio, and oxygen content, arising due to the difference in the degree of unsaturation of fatty acids from different sources [14]-[15]. European biodiesel that is produced from rapeseed oil of the canola oil family, is widely available in two features; namely in the form of 100% biodiesel (known as B100) and in the form of a mixture together with petro-diesel. Meanwhile, in the United States, a rising interest in producing and using biodiesel are directed to the usage of soybean oil as the main fuel, since the country being the largest producer of soybean oil in the world [16].

As for Malaysia, the preferred feedstock to be converted into biodiesel is Crude Palm Oil (CPO), since Malaysia currently being one of the main palm oil producers in the world. Therefore, many encouragements are given from the government for researchers to conduct their studies on palm oil, especially with regards to the feasibility and capability of CPO towards bio-fuel production.

2.2.1 Biodiesel Properties

Different combustion characteristics requirements are a result of different combustion processes applications. Several important parameters in fuel combustion are density, viscosity, and surface tension. This is because these parameters influence the pump and channel line plan, as well as giving huge impact on the spray injectors’ atomization nature, inevitably affects the performance of combustion and emission. Nevertheless, this is only applicable, given that these parameters are mainly focused on the droplet measurement dispersion issued from the injector nozzle, thus affecting the droplets’ vaporization, ignition and combustion. Note that each droplet size from the spray increases with the density, viscosity, and surface tension of the fluid, hence resulting the difference [17].

Table 2.1 shows a comparison of density and kinematic viscosity for different types of biodiesel. Based on the table, Biodiesel (B100) has different values of densities
and kinematic viscosities at test temperatures: 30°C and 40°C; respectively. As an example, the maximum and minimum density values are 897 kg/m³ for biodiesel from waste cooking oil, and 882.1 kg/m³ for biodiesel from Grapeseed Oil Methyl Ester (GOME) and soybean. This is implies that different feedstock will produce different fuel properties.

Table 2.2 shows the Malaysian palm oil biodiesel specifications and Malaysian petro-diesel standards, obtained from research conducted by Abdullah et. al. [18]. The table shows that the kinematic viscosity of biodiesel at 40°C and density at 15°C are within the range of 3.3 to 5.0 mm²/s and 860 to 900 kg/m³ respectively. The density and viscosity of B100 are much higher compared to the regular diesel used in oil burner, ranging from 2.5 to 3.5 mm²/s and 827 to 845 kg/m³ respectively.

Biodiesel fuel can be used in its pure form, however, biodiesel blends or blended with petroleum fuel are more commonly used. This is due to the fact that the use of biodiesel as the sole fuel requires modification on the burner system, since it tends to cause clogging on the fuel filters and injector holes. Apart from that, the formation of carbon deposits inside the combustion chamber also contributes to this preference. The most common biodiesel blends or mix; are referred as ‘B20’, indicate 20% biodiesel by volume, and 80% petroleum.
Table 2.1: Comparison of density and kinematic viscosity for various types of biodiesel [19]-[24]

<table>
<thead>
<tr>
<th>Types of biodiesel</th>
<th>Chemical formula</th>
<th>Test method</th>
<th>Kinematic viscosity at 40°C (mm²/s)</th>
<th>Test method</th>
<th>Density (kg/m³)</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower oil methyl ester (SOME)</td>
<td>CH₃₂ O₃</td>
<td>Calculation</td>
<td>3.8</td>
<td>ASTM D445</td>
<td>893.4</td>
<td>@60°C</td>
</tr>
<tr>
<td>Corn oil methyl ester (COME)</td>
<td>CH₃₃ O₃</td>
<td>Calculation</td>
<td>5.5</td>
<td>ASTM D445</td>
<td>884.4</td>
<td>@60°C</td>
</tr>
<tr>
<td>Rice bran oil methyl ester (ROME)</td>
<td>CH₃₄ O₄</td>
<td>Calculation</td>
<td>6</td>
<td>ASTM D445</td>
<td>888.5</td>
<td>@60°C</td>
</tr>
<tr>
<td>Olive oil methyl ester (OME)</td>
<td>CH₃₅ O₅</td>
<td>Calculation</td>
<td>5.3</td>
<td>ASTM D445</td>
<td>887.6</td>
<td>@60°C</td>
</tr>
<tr>
<td>GNPseed oil methyl ester (GOME)</td>
<td>CH₃₆ O₆</td>
<td>Calculation</td>
<td>5.2</td>
<td>ASTM D445</td>
<td>882.1</td>
<td>@60°C</td>
</tr>
<tr>
<td>Rapeseed methyl ester (RME)</td>
<td>-</td>
<td>-</td>
<td>4.478</td>
<td>ASTM D445</td>
<td>883.7</td>
<td>@15°C</td>
</tr>
<tr>
<td>Soy bean</td>
<td>-</td>
<td>-</td>
<td>5.8</td>
<td>ASTM D445</td>
<td>882.1</td>
<td>@60°C</td>
</tr>
<tr>
<td>Fatty acid methyl ester (FAME)</td>
<td>C₁₄-C₂₄ methyl esters</td>
<td>-</td>
<td>3.3-5.2</td>
<td>EN 14214</td>
<td>869-894</td>
<td>EN 14214</td>
</tr>
<tr>
<td>Palm oil biodiesel (PBO)</td>
<td>-</td>
<td>-</td>
<td>4.71</td>
<td>ASTM D445</td>
<td>884.4</td>
<td>@25°C</td>
</tr>
<tr>
<td>Palm biodiesel (palm methyl ester)</td>
<td>-</td>
<td>-</td>
<td>4.5</td>
<td>-</td>
<td>855</td>
<td>-</td>
</tr>
<tr>
<td>Waste cooking oil biodiesel</td>
<td>-</td>
<td>-</td>
<td>5.3</td>
<td>-</td>
<td>897</td>
<td>-</td>
</tr>
<tr>
<td>Soy bean crude oil</td>
<td>-</td>
<td>-</td>
<td>5.2</td>
<td>-</td>
<td>870</td>
<td>-</td>
</tr>
<tr>
<td>Waste cooking oil</td>
<td>-</td>
<td>-</td>
<td>4.56</td>
<td>ASTM D445</td>
<td>866</td>
<td>@60°C</td>
</tr>
<tr>
<td>Animal’s fats</td>
<td>CₓHₓOₓ</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>870</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.2: Different standards and specifications for palm biodiesel [18]

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>EN14214</th>
<th>ASTM D6751</th>
<th>Palm biodiesel PN</th>
<th>Low pour point PLPDO/PD B5</th>
<th>MS123: 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exene content (EN)</td>
<td>%</td>
<td>96.5</td>
<td>98.5</td>
<td>99.5</td>
<td>96.5±</td>
<td>98.5±</td>
</tr>
<tr>
<td>Density at 15°C</td>
<td>Kgm⁻³</td>
<td>860-900</td>
<td>878.3</td>
<td>870-890</td>
<td>841.9-845.9</td>
<td>841.9-845.9</td>
</tr>
<tr>
<td>Viscosity at 40°C</td>
<td>mm²/s</td>
<td>3.5-5.0</td>
<td>1.9-4.0</td>
<td>4.415</td>
<td>4 to 5</td>
<td>4.136-4.549</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>120&lt;</td>
<td>130.9</td>
<td>182</td>
<td>150-200</td>
<td>75-81</td>
</tr>
<tr>
<td>Cloud point</td>
<td>°C</td>
<td>Report</td>
<td>15.2</td>
<td>-18 to 0</td>
<td>14-16</td>
<td>18</td>
</tr>
<tr>
<td>Pour point</td>
<td>°C</td>
<td>15</td>
<td>-21 to 0</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Carbon residue on 10% distillation</td>
<td>%/m³</td>
<td>0.3&gt;</td>
<td>0.3&gt;</td>
<td>0.2</td>
<td>0.02-0.03</td>
<td>0.2</td>
</tr>
<tr>
<td>Acid Value</td>
<td>mg KOH/g</td>
<td>0.5&gt;</td>
<td>0.80&gt;</td>
<td>0.08</td>
<td>0.3&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Cetane index</td>
<td>-</td>
<td>51&lt;</td>
<td>47&lt;</td>
<td>58.3</td>
<td>53.0-59.0</td>
<td>51-57</td>
</tr>
<tr>
<td>Sulphur content</td>
<td>%/m³</td>
<td>0.001&lt;</td>
<td>0.001&lt;</td>
<td>0.001&gt;</td>
<td>0.001&gt;</td>
<td>0.0001±0.001±0.005</td>
</tr>
<tr>
<td>Sulphated ash content</td>
<td>%/m³</td>
<td>0.02&gt;</td>
<td>0.02&gt;</td>
<td>0.01</td>
<td>0.01&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Water content</td>
<td>mg/kg</td>
<td>0.03&lt;</td>
<td>0.03&gt;</td>
<td>0.03&gt;</td>
<td>0.02&gt;</td>
<td>0.001±0.001±0.005</td>
</tr>
</tbody>
</table>

PLPDO/PD B5 5% processed liquid palm oil (PLPDO) >95% petroleum diesel (PD)


The cloud point of biodiesel is generally higher than petroleum-based diesel and should be taken into consideration when blending.

Nevertheless, biodiesel blends such as B5, B10, B15, and B20 still have different values of density and kinematic viscosity, even after blending with regular diesel, as depicted in Figure 2.1. ‘B0’ stands for diesel fuel and ‘B100’ is for pure biodiesel, or
100% biodiesel. 'B5' indicates 5% biodiesel and 95% diesel fuel, whereas 'B20' is 20% biodiesel and 80% diesel. Refined, Bleached and Deodorized Palm Oil (RBDPO) has a high value of density at 40°C, compared with soy methyl and palm oil, but with a lower value of kinematic viscosity. Based on figure 2.1, a figure shown the relation between increase of percentage biodiesel with density at 40°C and Kinematic Viscosity at 15°C. The graph density at 40°C versus biodiesels (RBDPO, Soy Methyl and Palm Oil), the palm oil lead in term of increased rapidly with density. However, the palm oil decreased in early of viscosity but increased rapidly when near pure biodiesel (B100).

![Graph showing density and kinematic viscosity vs biodiesel ratio](image)

Figure 2.1: Density, Kinematic viscosity vs Biodiesel ratio for RBDPO [25], Soy methyl [24] and Palm oil [22]

2.3 Conventional and Modern Concepts of Diesel Combustion

A diesel fuel is part of petroleum row, which is also commonly termed as petro-diesel or fossil diesel, can be used to power up different types of vehicles. It is produced by blending crude oil that is refined by fractionate distillation between temperatures 200 °C and 350°C, at atmospheric pressure, similar to gasoline. The process for gasoline commences via ignition of the oxygen mixture by the engine cylinder. Being dense and oily as its characteristics, it is composed of a blend of different types of hydrocarbons,
including paraffin, naphthenes, olefins, and aromatics. The diesel engine operation starts when the piston travels up to the cylinder, in which causes the air to compress. During the top of the stroke, diesel fuel is injected into the cylinder and atomized and where it will start to ignite.

To meet future demands, the modern concept of diesel engines need to address the present of concerns of high soot, Particulate Matter, PM, and Nitrogen Oxide, NOx, emissions. These need to be significantly reduced in order to adhere with the emission legislation. Highly flexible high-pressure injection systems and high ambient temperature could overcome this problem. In direct injection diesel engines, fuel is injected into hot compressed air that is located within the combustion chamber. Due to the increasing gas temperature during compression, the combustion process is initiated by auto-ignition. The injection duration handles the start of combustion, in which the fuel quantity is injected per cycle piston motion, accordingly. Since the time available for mixture formation is brief, the fuel-air mixture will always consists of fuel-rich and lean regions, therefore, making it strongly heterogeneous [3].

Figure 2.2 illustrates the 3 phases carried out during the process of conventional diesel combustion. Phase 1 starts with the start of injection and will finish after ‘premixed combustion’. The direct injection of fuel into the cylinder typically commences with several degrees of crank angle, right before the ‘top dead center’ (TDC), where the exact duration will largely be influenced by engine speed and load. The amount of fuel that is injected per cycle influences the injection timing. Cold fuel jet will begin to mix with the hot compressed air, as soon as it starts to penetrate the combustion chamber. As the penetration increases, larger amount of hot air will be entrained. At this moment, the droplets will begin to vaporize and a sheath of vaporized heated fuel-air mixture will form around the jet’s periphery. Usually, temperature and reaction rate will increased immediately, thus producing the burning of complete fuel-air mixture that is formed during the ignition delay. In diesel combustion, fuel gasification, thermal cracking, and oxidation process will commence during the early stages of ignition delay period. This sudden combustion of well-prepared fuel-air mixture will cause a strong and sudden increase in heat release and cylinder pressure which is termed as ‘premixed peak’. However, the production of NOx will increase exponentially with
temperature, as soon this peak is reached. The heat that is released during the premixed combustion depends on the amount of fuel and evaporated during the ignition delay [3].

![Figure 2.2: Phases of the conventional diesel combustion process [3]](image)

Diffusion burning of diesel combustion describes Phases 2 and 3, shown in Figure 2.2. During Phase 2, the injected fuel drops will heat up. This is caused by the entrainment of hot air and combustion products into the jet, near the nozzle. As the evaporated fuel penetrates the spray further, it breaks down into small molecules, which undergoes partial oxidation, due to the lack of sufficient oxygen within the hot spray cloud [26]. During the described mixing-controlled Phase 2 the burning rate is only limited by mixture of fuel fragments and air. Thus, the time taken for the chemical reactions to occur will be much faster.

Subsequently, the final oxidation of the remained unburned and partially oxidized fuel fragments, which includes most of the soot particles, takes place during Phase 3. However, due to the decrease in gas temperature during expansion stroke as
well as the strong decrease in oxygen content, the chemical reactions become slower thus becoming the limiting factor to stop the entire process.

2.3.1 Definition of Ignition Delay

W. W. Pulkrabek [27] defined that increasing the temperature of an air-fuel mixture high enough to cause self-ignition without using a spark plug or any other igniter will lead to a certain temperature, known as the Self-Ignition Temperature (SIT). If a mixture of air-fuel is heated to a temperature that is less than SIT, it will eventually cool off, in which no ignition will occur after compression. On the other hand, after the compression is completed, and the mixture is heated greater than SIT, self-ignition will occur after a certain short time delay. That is known as Ignition Delay (ID).

In diesel combustion engines, the combustion process progresses in a naturally heterogeneous manner. After fuel is injected into hot compressed air, within a short period of time, diesel spray injection will spontaneously ignite. The duration of the ignition delay is one of the determining factors for the rapid rise of the initial burning stage. Therefore, this will cause a great effect on the combustion process and exhaust emissions [2]. K. Olawole [28] discussed that in Compression Ignition (CI) engines, physical and chemical processes govern the ignition and combustion activities in the engines. However, the ignition delay time between the injection duration and ignition outcome, depends largely on both; the physical delay for mixture formation as well as the chemical delay that leads to thermal decomposition [27]. M. Shahabuddin et. al [29] mentioned the engine design and performance of diesel engine is exerts very great effect by delay period. Functionally, the ignition delay can be divided into two parts, such as the physical delay and chemical delay as shown in Figure 2.3.
Figure 2.3: Extended view of ignition delay [30]

Physical delay ($\tau_1$) is defined as the time between the beginning of injection and the attainment of chemical reaction conditions. During this period, the fuel is atomized, vaporized, mixed with air and raised to auto-ignition temperature. Viscosity governs the physical delay of fuel combustion process, for low viscosity fuels, the physical delay is small. For Chemical delay ($\tau_2$), during this period reactions start slowly and then pick up until inflammation or ignition takes place. In fact, chemical delay usually is longer than the physical delay. However, it based on the temperature of ambient. Chemical reaction is faster at higher ambient temperatures thus physical delay becomes longer than the chemical delay [29].

Figure 2.4 describes a typical pressure trace obtained during a test run in which, as soon as the piston is released, the gaseous mixture is compressed to $P_2$ in an isentropic process. Subsequently, when the piston is sparked, the event is sequenced between 20 to 30 ms, following to an end of the compression process where there will be a small amount of pressure decreased, as a result from heat transfer to the combustion chamber walls, $(P_2 - P_1)$; in which during this period is known as the ignition delay times ($\tau_1$ and $\tau_2$) [31]. Based on Figure 2.4, $\tau_1$ (corresponding to physical delay) represents the period...
of time between the start of injection, until the moment where the piston pressure, for an acting spray separates from an identical spray that is injected into an inert nitrogen atmosphere. The time period from the end of time $t_1$ reaching until a continuous pressure curve across the interpolated straight line is time $t_2$ (corresponding to chemical delay) that represents the amount of heat loss from the combustion chamber. The combination between $t_1 + t_2$ is defined as the ignition delay time that is used to characterize diesel fuel. Fuel is injected into air with variant temperature and pressure conditions, where as soon as the pressure rises, the ignition will start to decline, in which cracking and gasification as well as heat loss are observed from surrounding air[32].

![Combustion process and Ignition delay](image.png)

Figure 2.4: Time history of pressure in combustion chamber [31]

### 2.3.2 Effect of Injection Pressure and Ambient Temperature on Ignition Delay

M. Mohon Roy et al. [33] explained that high pressure fuel injection induces a higher level of fuel dispersion with good atomization and fuel-air mixing during compression. High injection pressure provides a better evaporation of small fuel particles and consistently causing the ignition delay to become longer [34]. Therefore, less fuel
adhering to the combustion chamber walls will eventually produce lower emissions. This is because of the drop in fuel adhering to the combustion chamber walls, owing to the longer ignition delay and improved mixture formation. G. R. Riva et al. [35] mentioned that the variation in injection pressures (within the tested range) scarcely affects the ignition delays. Both chamber temperature and density increments will significantly shorten the ignition delays, thus causing a monotonic effect. Figure 2.5 depicts the ignition delay as a function of injection time, with various injection pressures and engine loads for biodiesel and diesel fuel.

The delay period is seen to be different when diesel and biodiesel were used individually during combustion process. The increment of injection pressure could reduce the ignition delay regardless of fuel type, injection timing, as well as engine load. This is because higher injection pressure improves fuel atomization and enhances evaporation of fuel droplets and the mixing process with the ambient air. However, the ignition delay of biodiesel requires a longer time, compared to diesel fuel, even though biodiesel causes a shorter ignition delay due to a slightly higher cetane number. This is because biodiesel contains a higher fuel viscosity, therefore generates higher friction around the injector needle [36].
Figure 2.5: Comparison of ignition delay with different injection pressures, injection timings and engine loads: (a) low load, (b) high load condition [36]

Figure 2.6 shows the definition of the chemical ignition delay, with respect to temperature. The chemical ignition delay is defined as the time period from the start of reaction modeling until the rate of change of temperature (dT/dt) reaches its maximum value, which could be referred as the ‘explosive chain branching’ event. Based on Figure
2.6, it can be seen that the equivalence ratios for both Palm Oil and Waste Cooking Oil changes with different injection pressures: 100 MPa, 200 MPa, and 300 MPa respectively. It is noted that in the designated simulation, ambient air temperature during propagation of evaporating spray liquid length corresponds to the point where ignition is expected to occur. Therefore, the ambient temperature is 850 K, which implies that the ambient temperature could have dropped as a result of vaporization of fuel in air, at the ignition location [28].

Figure 2.6: Temporal variation in model predicted ambient temperature [28]
REFERENCES


[34] Amir Khalid, and B. Manshoor, “Effect of High Injection Pressure on Mixture Formation, Burning Process and Combustion Characteristics in


