Diesel and Bio-diesel Fuel Deposits on a Hot Wall Surface

A THESIS
Submitted by

YUSMADY BIN MOHAMED ARIFIN

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Under the guidance of

PROFESSOR MASATAKA ARAI, Ph. D. Eng.

DEPARTMENT OF MECHANICAL SYSTEM ENGINEERING
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JAPAN

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Finally, I also would like to thank to my mother Ampuan Azizah and my beloved wife Nor Hayati for her patience, cooperation and moral support.
Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

Signature:

Name: Yusmady bin Mohamed Arifin

Student No.: 06812272

Date:
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List of abbreviations

Al  Aluminum
A/F  Air/Fuel
ATDC  After top dead center
$ave$  Average
B5  JIS No. 2 diesel fuel blend with 5%wt B100
B20  JIS No. 2 diesel fuel blend with 20%wt B100
B50  JIS No. 2 diesel fuel blend with 50%wt B100
B100  100% Palm oil methyl ester (PME) based bio-diesel fuel
B100C  100% Coconut oil methyl ester (CME) based bio-diesel fuel
BDF  Bio-diesel fuel
BMEP  Brake mean effective pressure
BSFC  Brake specific fuel consumption
BTDC  Before top dead center
C  Carbon
Ca  Calcium
CA  Crank angle
CME  Coconut oil methyl ester
CN  Cetane number
CO  Carbon monoxide
CR  Compression ratio
Cu  Copper
CCD  Combustion chamber deposit
CPO  Crude palm oil
DF  JIS No. 2 diesel fuel
<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>DI</td>
<td>Direct injection</td>
</tr>
<tr>
<td>DO</td>
<td>Dodecane: C\textsubscript{12}H\textsubscript{26}</td>
</tr>
<tr>
<td>DFP</td>
<td>Philippine National Standard diesel fuel</td>
</tr>
<tr>
<td>DIR\textsubscript{o}xidation</td>
<td>Differential infrared of oxidation (Degree of oxidation)</td>
</tr>
<tr>
<td>DF+1%L</td>
<td>JIS No. 2 diesel fuel blend with 1%wt lubricant oil (SAE 30)</td>
</tr>
<tr>
<td>DF+2%L</td>
<td>JIS No. 2 diesel fuel blend with 2%wt lubricant oil (SAE 30)</td>
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<td>ET</td>
<td>Evaporation test</td>
</tr>
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<td>EDT</td>
<td>Engine deposition test</td>
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<tr>
<td>EGR</td>
<td>Exhaust gas circulation</td>
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<td>FAME</td>
<td>Fatty acid methyl esters</td>
</tr>
<tr>
<td>Fe</td>
<td>Ferrum</td>
</tr>
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<td>FBP</td>
<td>Final boiling point</td>
</tr>
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<td>H</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>H/C</td>
<td>Hydrogen/Carbon</td>
</tr>
<tr>
<td>HCCI</td>
<td>Homogeneous charge compression ignition</td>
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<tr>
<td>HSDT</td>
<td>Hot surface deposition test</td>
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<tr>
<td>IBP</td>
<td>Initial boiling point</td>
</tr>
<tr>
<td>IDI</td>
<td>Indirect injection</td>
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<tr>
<td>LHV</td>
<td>Low heating value</td>
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<td>Mg</td>
<td>Magnesium</td>
</tr>
<tr>
<td>MEP</td>
<td>Maximum evaporation rate point</td>
</tr>
<tr>
<td>MEXA</td>
<td>Particulate analyzer: HORIBA, MEXA-1370PM</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>Oxides of nitrogen</td>
</tr>
<tr>
<td>OD</td>
<td>Typical diesel fuel</td>
</tr>
<tr>
<td>ORI</td>
<td>Octane requirement increase</td>
</tr>
<tr>
<td>OHV</td>
<td>Overhead valve</td>
</tr>
<tr>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>PBA</td>
<td>Polybutane amine-based additive</td>
</tr>
<tr>
<td>PEA</td>
<td>Polyether amine-based additive</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
</tr>
<tr>
<td>PME</td>
<td>Palm oil methyl ester</td>
</tr>
<tr>
<td>PNS</td>
<td>Philippine National Standard</td>
</tr>
<tr>
<td>R</td>
<td>Radical</td>
</tr>
<tr>
<td>RME</td>
<td>Rapeseed methyl ester</td>
</tr>
<tr>
<td>SI</td>
<td>Spark ignition</td>
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<tr>
<td>SMD</td>
<td>Sauter mean diameter</td>
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Nomenclature

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<thead>
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<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tr>
<td>SOF</td>
<td>Soluble organic fraction</td>
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</tr>
<tr>
<td>Swe Mk1</td>
<td>Swedish class 1 diesel</td>
<td></td>
</tr>
<tr>
<td>TDC</td>
<td>Top dead center</td>
<td></td>
</tr>
<tr>
<td>THC</td>
<td>Total hydrocarbon</td>
<td></td>
</tr>
<tr>
<td>ULSD</td>
<td>Ultra low sulphur diesel</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
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<td>A</td>
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<tr>
<td>b</td>
<td>Constant</td>
<td>[-]</td>
</tr>
<tr>
<td>D_d</td>
<td>Diameter of a droplet</td>
<td>[mm]</td>
</tr>
<tr>
<td>D_o</td>
<td>Initial droplet diameter (in literature)</td>
<td>[mm]</td>
</tr>
<tr>
<td>d_o</td>
<td>Initial droplet diameter (in literature)</td>
<td>[mm]</td>
</tr>
<tr>
<td>dQ/dθ</td>
<td>Heat release rate</td>
<td>[J/deg.]</td>
</tr>
<tr>
<td>L_h</td>
<td>Needle tip to the center of hot plate distance</td>
<td>[mm]</td>
</tr>
<tr>
<td>M_R</td>
<td>Total deposits on a hot surface</td>
<td>[g]</td>
</tr>
<tr>
<td>M'_R</td>
<td>Total deposits on the plug</td>
<td>[g]</td>
</tr>
<tr>
<td>m_inj</td>
<td>Mass of a single shot injection fuel</td>
<td>[g/injection]</td>
</tr>
<tr>
<td>M_D</td>
<td>Total mass of fuel droplets</td>
<td>[g]</td>
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<tr>
<td>M_d</td>
<td>Accumulated mass of fuel droplets</td>
<td>[g]</td>
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<tr>
<td>m_D</td>
<td>Mass of a single fuel droplet</td>
<td>[g]</td>
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<tr>
<td>m_Dep</td>
<td>Deposit mass (in literature)</td>
<td>[kg]</td>
</tr>
<tr>
<td>N_inj</td>
<td>Number of injections</td>
<td>[-]</td>
</tr>
<tr>
<td>N_D</td>
<td>Number of droplets impinged</td>
<td>[-]</td>
</tr>
<tr>
<td>N_e</td>
<td>Engine speed</td>
<td>[rpm]</td>
</tr>
<tr>
<td>n_rev</td>
<td>Engine revolutions</td>
<td>[rpm]</td>
</tr>
<tr>
<td>n_rev</td>
<td>Engine speed (in literature)</td>
<td>[min⁻¹]</td>
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<td>p_Ch</td>
<td>Charge air pressure (in literature)</td>
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<td>p_ex</td>
<td>Exhaust gas pressure (in literature)</td>
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<td>p_me</td>
<td>Mean effective pressure (in literature)</td>
<td>[MPa]</td>
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<td>P_intake</td>
<td>Intake pressure (in literature)</td>
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<td>--------</td>
<td>-------------</td>
<td>------</td>
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<tr>
<td>( q )</td>
<td>Instantaneous heat flux (in literature)</td>
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<td>( R_z )</td>
<td>Roughness of the hot surface (in literature)</td>
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<tr>
<td>( r )</td>
<td>Coefficient of correlation</td>
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<tr>
<td>( T_h )</td>
<td>Heater temperature</td>
<td>[°C]</td>
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<td>( T_{MEP} )</td>
<td>MEP temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_i )</td>
<td>Indicated temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_s )</td>
<td>Surface temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_d )</td>
<td>Surface temperature of deposits</td>
<td>[°C]</td>
</tr>
<tr>
<td>( T_p )</td>
<td>Plug temperature</td>
<td>[°C]</td>
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<tr>
<td>( T_c )</td>
<td>Cylinder head temperature</td>
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<td>Ceiling temperature of the test chamber (in literature)</td>
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<td>( T_{deposit} )</td>
<td>Surface temperature of deposit</td>
<td>[°C]</td>
</tr>
<tr>
<td>( t_g )</td>
<td>Running time</td>
<td>[hour]</td>
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<tr>
<td>( T_{Wall} )</td>
<td>Surface temperature of clean wall</td>
<td>[°C]</td>
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<td>( T_W )</td>
<td>Wall temperature (in literature)</td>
<td>[°C]</td>
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<tr>
<td>( t_w )</td>
<td>Surface temperature at center of the hot surface (in literature)</td>
<td>[°C]</td>
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<td>( T90 )</td>
<td>90% distillation temperature</td>
<td>[°C]</td>
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<tr>
<td>( \Delta T_{SUB} )</td>
<td>Sub-cooled temperature ((T_S-T_{MEP}))</td>
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<td>( W )</td>
<td>Deposit mass (in literature)</td>
<td>[mg]</td>
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<tr>
<td>( X )</td>
<td>Percentage of DF in blended fuel</td>
<td>[%]</td>
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<tr>
<td>( z )</td>
<td>Vertical distance from the hot surface (in literature)</td>
<td>[mm]</td>
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**Greek letters**

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( \alpha )</td>
<td>Constant for initial deposition</td>
<td>[-]</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Exponential index for deposition development</td>
<td>[-]</td>
</tr>
<tr>
<td>( \gamma_m )</td>
<td>Surface tension (in literature)</td>
<td>[mN/m]</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Excess air-fuel ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Crank angle</td>
<td>[deg.]</td>
</tr>
<tr>
<td>( \theta_{nj} )</td>
<td>Injection timing</td>
<td>[deg.]</td>
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<tr>
<td>( \rho_{fuel} )</td>
<td>Density of fuel</td>
<td>[kgm⁻³]</td>
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<tr>
<td>( \rho_m )</td>
<td>Density (in literature)</td>
<td>[g/mL]</td>
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<tr>
<td>( \tau_{life} )</td>
<td>Droplet lifetime</td>
<td>[sec]</td>
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<tr>
<td>( \tau_e )</td>
<td>Droplet lifetime (in literature)</td>
<td>[sec]</td>
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<tr>
<td>Symbol</td>
<td>Description</td>
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<td>$\tau_{\text{imp}}$</td>
<td>Impingement interval</td>
<td>[sec]</td>
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<tr>
<td>$U_p$</td>
<td>Piston temperature (in literature)</td>
<td>[°C]</td>
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<tr>
<td>$\nu_m$</td>
<td>Kinematics viscosity (in literature)</td>
<td>[cSt]</td>
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<tr>
<td>$\nu_{\text{Blend}}$</td>
<td>Kinematics viscosity of DF blend with SAE30 lubricant</td>
<td>[mm$^2$/s]</td>
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</table>
Abstract

Deposit formation in the combustion chamber of an engine is a complex phenomenon that causes various engine problems such as reduced engine performance, increased emissions and causes engine damage for diesel engines. The utilization of bio-diesel fuel further increases the tendencies of deposit formation in the engine due to its higher viscosity and distillation temperature compared to diesel fuel. The aim of this study is to clarify fuel deposition in an engine using a simplified method which is referred to as the hot surface deposition test (HSDT). The HSDT is also used to simulate and investigate deposit formations for diesel fuels and bio-diesel fuels on the wall in the combustion chamber instead of using the engine deposition test (EDT). HSDT and EDT showed that both have similar tendencies in deposit development and soot fraction in deposits. HSDT is considered as an initial research step in developing a simplified method for engine deposit investigation and it is capable of differentiating the deposit development among various types of fuels. The deposit development on a hot surface depended on the droplet impingement interval, hot surface temperature, types of fuel, deposit properties, initial stage of deposition, overlapping conditions and competition phenomena during deposit formation, such as a cooling effect, heat transfer effect and chemical reaction effect. These factors determine the existence of wet conditions and the amount of deposits accumulated. Different hot surface temperatures showed different droplet-surface interactions, evaporation lifetimes and wet/dry conditions where various deposit development features resulted. Palm oil methyl ester (PME) which is refer to as 100% palm oil methyl ester based bio-diesel fuel (B100) and its blends (B50, B20 and B5) produced a higher development rate of deposits compared to diesel fuel (DF). Less amount of DF deposits was obtained due to an absence of bio-diesel fuel components, and non-overlapping and dry deposit conditions. Philippine National Standard diesel fuel (DFP) having 1% coconut oil methyl ester (CME) in composition, showed a greater deposit development rate compared to DF, which resulted in a relatively large amount of deposits for DFP. However, for bio-diesel fuels, coconut oil methyl ester (CME) which is referred to as 100% coconut oil methyl ester based bio-diesel fuel (B100C) obtained a slower deposit development rate compared to B100, although the test conditions were changed. Due to the lower value of maximum evaporation rate point (MEP) and shorter droplet lifetime before MEP, utilization of B100C had a greater potential in reducing deposit formation compared to B100.
Chapter 1

Engine deposit research: A review of the current literature

1.1 Introduction

For many years diesel engines have been commonly used in transportation due to their advantages over gasoline engines such as high power/weight ratio, high thermal efficiency, simple mechanisms, rigid structure, low breakdown rate and high fuel economy. Their higher efficiency allows less fuel to be used for the same distance. This low fuel consumption is the main reason for the popularity of diesel engines. However, the pollutants emitted from diesel engines during combustion have been considered the major air pollution source throughout the world. Instead of environment pollution, another problem involved with diesel fuels is the increasing price of oil. The phenomenon gives a major impact on world-wide economic development.

Oil price and air pollution are now becoming two of the main driving forces of new energy development. Many researchers have been trying to develop new types of fuel in order to solve problems involved with diesel fuel. Some of them emphasize the potential of palm oil ester, referred to as bio-diesel fuels considered as substitutes for diesel fuels. This can be achieved by forming methyl (or ethyl) esters of palm oils and by using these esters as fuels. Since the viscosity and volatility of these esters, referred to as bio-fuels, are comparable to those of diesel fuel, they can be used for direct injection (DI) diesel engines without modification [1].

Masjuki, et. al. [2] used palm-oil methyl ester and its blends with conventional diesel fuel in an automobile diesel engine and found that the engine performances obtained were comparable with diesel fuel. Bio-diesel fuel and its blends are also capable of reducing emissions. Moreover, the cetane rating, which is a measure of the quality of ignition, obtained with palm oil methyl ester was higher than that of commercial diesel fuel. Although bio-diesel fuels have advantages in reducing emissions and their blends with diesel fuel showed comparable engine performance, their properties and combustion behaviors in an engine have not been well understood. Bio-diesel fuel usage in engines also causes various problems as mentioned by Senda, et. al. [3] in Table 1-1.
Table 1-1 Problems and causes in using bio-diesel fuel (BDF) [3]

<table>
<thead>
<tr>
<th>Problems using BDF</th>
<th>Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterioration of cold start</td>
<td>Poor low-temperature fluidity</td>
</tr>
<tr>
<td>Exhaust of smoke at cold start</td>
<td>Exhaust of unburned elements</td>
</tr>
<tr>
<td>Deposits in combustion chamber</td>
<td>Incomplete combustion of high boiling components</td>
</tr>
<tr>
<td>Plugging of fuel filter</td>
<td>Deposit of glycerin and alkali catalysts in fuel</td>
</tr>
<tr>
<td>Degradation of fuel</td>
<td>Auto-oxidation of fuel</td>
</tr>
<tr>
<td>Degradation of rubber product</td>
<td>Auto-oxidation of fuel, Swelling of rubber by oxygen</td>
</tr>
</tbody>
</table>

To expand the utility of bio-diesel fuel, many studies on the properties and combustion behaviors of bio-diesel fuels are still needed. One of the important studies for the utilization of bio-diesel fuel is basic research on depositions in engines. Since the deposits in an engine cause surface heat transfer alteration [4, 5], engine knock [6], hydrocarbon emissions [7, 8], and reduce engine lifespan, deposits resulting from bio-diesel fuel should be calculated and countermeasures for its reduction should be developed to ensure the long term use of the engine.

Furthermore, different types of bio-diesel fuels have different properties and show different combustion behaviors. In terms of properties, bio-diesel fuels have less thermal stability, higher values of density and viscosity compared to typical diesel fuel, thus those fuel characteristics increase the possibility of increasing deposit formation in engines.

In this chapter, various aspects of engine deposit available in the current literature is discussed in order to understand the effects and factors of deposit formation in engines. Understanding deposit mechanisms is crucial for finding effective deposit prevention measures. The information and knowledge obtained from the literature can help to enhance our understanding in deposit formation and the deposit development of bio-diesel fuels in this study.

1.2 Bio-diesel fuel

Bio-diesel fuel is defined as fatty acid methyl ester (FAME), which is the result of the reaction of fatty acids with methyl alcohol [9] through a process called transesterification. Figure 1-1 illustrates the transesterification process and the chain structure of fatty acid methyl ester [10]. This type of fuel may be substituted for diesel fuel in engines. Nowadays, bio-diesel fuel has been
gaining attention as an alternative for diesel fuel. Diesel engines that use bio-diesel fuel reduce green house gas emission and save fossil fuel. However at this moment, only 5% and 20% bio-blended diesel fuels are practical for use in vehicles. In terms of its properties, compared to typical diesel fuel, it still has higher viscosity and higher distillation properties that can lead to the formation of carbon deposits in the combustion chamber, which has a negative effect on engine performance.

![Diagram of triglyceride and methyl esters](image)

**Figure 1-1** Transesterification of fatty acids and typical chain structure of fatty acid methyl esters [10]

Bio-diesel fuels have a high and narrow distillation range [11] and the final boiling point (FBP) is identical to diesel fuel in some cases [12]. The bio-diesel fuel distillation properties are shown in **Figure 1-2**. The high and narrow range of distillation properties caused the bio-diesel fuel is easy to condense and forms liquid film on the wall surface in the combustion chamber. The formation of liquid film increases the tendencies to form deposits on the wall. As mentioned by Zheng, et. al. [12], the low volatility and high viscosity of bio-diesel fuels may result in poor fuel atomization and air/fuel mixing due to the formation of the larger size of fuel droplets during fuel atomization in engines. Furthermore, different types of bio-diesel fuels have different properties and combustion behaviors. For example, palm oil methyl ester (PME) and coconut oil methyl ester (CME) bio-diesel fuels, both have different properties and combustion behaviors. According to Ejim, et. al. [13], PME has a higher value of viscosity and surface tension compared to CME. Hence, during engine operation, spray vaporization for PME and CME are different due to the bigger size of PME droplets formed compared to CME. One of the parameters that is effected due to bigger size of fuel droplets is the ignition delay during the combustion process. The ignition delay will increase for PME compared to CME, where its droplets
require more time to vaporize.

![Figure 1-2 Distillation profiles for diesel and bio-diesel fuels [12]](image)

Distillation properties, particulate formation propensity and the value of viscosity for bio-diesel fuel are the factors that effect the deposit formation. However, the distillation property is the most dominant property that determines the amount of deposit for different types of fuels.

Kalam, et. al. [5] also mentioned that the used of palm oil bio-diesel fuel in diesel engines faced some degree of difficulty such as incomplete combustion, including piston ring sticking and carbon deposits caused by the high viscosity and density of fuel plugging the injector jets, which in turn caused poor injection, fuel atomization and vaporization.

Konno, et. al. [11] investigated carbon-deposit formation characteristics and the formation factors of diesel engines fueled with rapeseed methyl ester (RME) and found that the carbon deposit of RME accumulates rapidly, and has a long term periodic break-off compared to diesel fuel as shown in Figure 1-3.

The physical and chemical properties of bio-diesel fuel influence the characteristics in the engine’s combustion chamber. In terms of bio-diesel fuel’s influence on injection characteristics, Yamane, et. al. [10] found that the utilization of bio-diesel fuel shortens spray penetration compared to diesel fuel. Thus, the air-fuel mixing process was relatively poor for the bio-diesel fuels. The result obtained by Yamane, et. al. [10] was for non-evaporated spray. Bio-diesel spray penetration is different for evaporated spray as shown by the study conducted by Senda, et. al. [3]. In this study, greater spray penetration was obtained compared to diesel fuel. This is due to higher density and also a longer time for evaporation.
for bio-diesel fuel compared to diesel fuel, which resulted in a greater momentum of fuel spray to axial direction. Although both Yamane, et. al. [10] and Senda, et. al. [3] used almost similar properties of recycled cooking oil methyl ester bio-diesel fuel, their different test environment gave different results of spray penetration for bio-diesel fuel compared to typical diesel fuel.

![Figure 1-3 Relation between wall temperature $T_w$ and maximum and minimum weights of deposit [11]](image)

The properties of different types of bio-diesel fuel are different from typical diesel fuel that cause different combustion behavior for bio-diesel fuels. To reduce the differences, a small amount of bio-diesel fuel (less than 20%) can be blended with diesel fuel in order to obtain behavior similar to diesel fuels. Rakopoulus, et. al. [14] mentioned that by blending 10% and 20% bio-diesel fuel with neat diesel fuel, the injection rate or the macroscopic behavior of the spray is almost identical to neat diesel fuel for the same engine operating conditions (injection timing, speed and load). This study also showed that all 10% and 20% of various bases of bio-diesel fuels blended with diesel fuel obtained higher amounts of HC emission compare to diesel fuel during medium load of engine operation. Although at high load engine operation, the tendencies of the bio-blended diesel fuels to emit HC were similar to diesel fuel, some of the bio-blended diesel fuels still obtained more HC emission as shown in Figure 1-4. HC emission is related to incomplete combustion process resulting in unburned hydrocarbons. Thus, the increases of HC emission for these bio-blended diesel fuels also show the tendencies of the fuel to form more deposits in the engine.

Sinha, et. al. [15] investigated the effects of different blends of rice-bran oil methyl ester (10% and 20%) to combustion in engines. In the study, cumulative
heat release for bio-diesel blends decreases as the proportion of bio-diesel is increased in the blend, owing to the lower heating value of bio-diesel fuel. Further, Sinha, et. al. [15] mentioned that more fuel is required in the case of bio-diesel blends because the calorific value of these blends is lower than that of diesel and caused longer combustion duration for bio-diesel blends.

![Figure 1-4](image)

**Figure 1-4** Emitted total unburned hydrocarbons (HC) for diesel fuel, bio-blended diesel fuels and vegetable oil blends of various origins for medium load (a) and high load operation (b) [14]

1.3 Engine deposits

Deposits or carbon deposits may be defined as heterogeneous mixtures made up of carbon residue (ash), carbonaceous mixtures (soot) and oxygenated resinous organic material that bind together as mixtures [16]. It can also include any number of materials, excess, or residue that is gradually grown or accumulated on critical parts of an internal combustion engine [17]. Engine parts in the combustion chamber such as the cylinder head, piston, intake and exhaust valves, and injector tip are common parts where engine deposits regularly accumulate, as shown in **Figure 1-5**.

Deposits on the various parts of an engine cause substantial impact on engine performance, fuel economy, cold-start, warm-up drivability, and exhaust emission.
through various problems such as lowering the fueling rate, restricting air flow, increasing compression ratio, altering spray pattern, inducing knock, degrading thermal conductivity, and reducing catalyst reactivity [18]. Further, a new field problem associated with flakes of combustion chamber deposit getting trapped on the exhaust valve seat has been reported by Kalghatgi [19]. The deposit flakes cause difficulties in start-up and poor driveability, increase in hydrocarbon emissions and rough running [20, 21], and eventually, will cause a loss of compression in the cylinder.

![Figure 1-5 Deposits on various parts of the combustion chamber](image)

In terms of engine damage, deposits caused wear and fouling of engine parts, especially on piston and cylinder surfaces as mentioned by Muzikus, et. al. [22] and Artemiev [23]. Piston deposits can cause ring sticking and scuffing which interferes with the normal operation of an engine [24]. Eilts [25] mentioned that deposit formation in the engine causes serious damage in direct injection diesel engines during long low load operation. In modern engine design, deposit formation in the engine increases unburned HC due to adsorption and desorption of HC by the deposits. NOx emissions also increase due to the insulation effect and heat storage of the deposits that increase the gas temperature in the combustion chamber. In advanced engine technology systems such as injection systems that have small injector holes with high injection pressure, deposit formation is more significant. Even small amounts of deposits can disturb the system’s performance.
1.3.1 Deposit origin

In general, the main contributor of combustion chamber deposits may derive from fuel, lubricant oil or from a combination of both. However, the domination of fuel and lubricant oil in contributing deposits depend on various factors such as engine type and engine parts location in the combustion chamber. As mentioned by Lepperhoff, et. al. [26], deposit locations at high temperature areas of an engine primarily result from nonmetallic residuals from evaporating or burning fuel and/or lubricants.

Different studies suggest different levels of domination of fuel and lubricant oil in deposits. Some studies found that lubricant oil is the primary contributor of combustion chamber deposits (CCD) [7, 27-29]. The presence of lubricant oil components and elements such as ash residues, fractions of inorganic materials, and high boiling point hydrocarbons found in the studies proved the involvement of lubricant oil in deposit formation.

Fukui, et. al. [29] investigated the influence of fuel and lubricant oil on the CCD weight in a single cylinder two-stroke SI engine, where the engine’s test was operated with gasoline and i-octane as fuel and oil A and B as lubricant oil. The result in Figure 1-6 shows that the influence of lubricant oil on CCD accumulation in the engine was found to be larger than that of unsaturated hydrocarbon included in fuel. Diaby, et. al. [30] conducted an investigation on first ring groove deposits in a four-cylinder diesel engine. The deposit at the first ring grooves in the study were analyzed for their chemical components by using X-ray dispersive energy equipment, which found no elements that could be related to fuel components. Thus, the study has shown that the deposits of the first ring grooves of the investigated diesel engine are mainly carbonaceous and result principally from the lubricant degradation, where a large proportion of metallic elements were found from the analysis. It appeared that the degradative oxidation of the lubricant induces polymerization reactions, leading to the formation of a varnish acting as a binder which can ensure cohesion between carbon particles and metallic particles of wear, worsening the cycle of lubricant degradation. In another study [31], the soot produced from diffusion burning of the diesel fuel was found to contribute only 20% to deposits, the remainder being lubricating oil-derived.

In some types of diesel engines, the engines are lubricated by the diesel fuel itself, so the lubricant is no longer a source for metal ions in deposits in the engine [27]. Diesel fuel today contains a variety of acidic components such as fatty
acids, with different degrees of un-saturation that are commonly used as lubricity additives in diesel fuel. Such acids have been shown to readily react with metal ion impurities in the fuel to form metal soaps. As mentioned by Ullmann, et. al. [27], these metal soaps have been associated with the formation of nozzle tip/spray-hole deposits.

![Image](image.png)

**Figure 1-6 Influence of fuel and lubricant oil on CCD formation [29]**

Previous research conducted by Ra, et. al. [32] has focused on soot formation and deposition on the cylinder wall (piston bowl and top surface, cylinder head and parts of the cylinder liner exposed to combustion gases) that originate from the injected fuel. In the research, the effect of piston ring pack crevice flow and lubricant oil vaporization on heavy-duty diesel engine was investigated numerically, where various models such as combustion, soot formation, deposition and oil vaporization models were used. However, a substantial amount of soot deposition is found in crevice regions, including the piston ring pack, which indicates that crevice-borne hydrocarbon fuels may play an important role in deposit formation on piston/crevice surfaces. Devlin, et. al. [24] investigated deposits on a Sequence IIIG piston. The result showed that the deposit formed on the piston top and on the second land of the piston was fuel-derived. The contribution of lubricant in the deposit composition was less than 17%.

In terms of fuel’s effect on injector deposits in diesel engines, Leedham, et. al. [33] suggested that trace amounts of metals could be implicated in the deposit formation mechanism. The engine testing carried out in the study showed that base fuel did not have significant levels of deposits. However, in the presence of trace amounts of zinc, a substantial level of deposits is generated. The lubricity additives may play a role in the uptake of zinc into the fuel. The ester lubricity additives do not affect the zinc levels of the fuel, whilst the acid lubricity agent appeared to be implicated in the uptake of the zinc as shown in Figure 1-7. The figure shows the effect of various lubricity additives in two different fuels, which
are Swedish Class 1 Diesel (Swe Mk1) and Ultra Low Sulphur Diesel (ULSD). It appeared that lead (Pb) as well as zinc (Zn) was susceptible to absorption into the fuel, whilst the other metals were not detected. The results confirmed the earlier studies; the ester lubricity agents were not picking up metals, whilst the acid technology was consistently picking up lead and zinc into the fuel.

Further, in terms of fuel contribution to deposit formation, Ebert [34] noted that unburned fuel, in combination with crankcase oil, oxidized and condensed, producing varnish and sludge. Another study conducted by Cloud, et al. [35] suggested that sulphur is converted to sulphur trioxide which in turn attacks the lubricating oil producing sludge and eventually varnish-type deposits. Thus, from this evidence, there are many factors involved in fuel and lubricant domination in combustion chamber deposits.

![Figure 1-7 Zinc uptake by lubricity additives in two fuels [33]](image)

### 1.3.2 Deposit characteristics

#### (1) Deposit structure

The structure of engine deposits is sensitive to many parameters, including base fuel composition, engine operating temperatures, and the presence of deposit control additives in the fuel [36]. Physical features of deposits contribute to various effects in the combustion chamber such as heat transfer alteration and HC source. The porous structures of deposits activate the fuel storage mechanism and play an important role on the HC level [18]. Furthermore, deposit masses were found to correlate well with HC emissions as mentioned in theoretical work done by Eilts [25].
Guralp, et. al. [17] investigated properties of the deposits layer, since it is the combustion chamber deposit coating that affects heat transfer and combustion. The porous volumes found in the deposit material presented the potential for intra-material heat transfer through convection and radiation. Given that the chemical structure of deposits varies over time and is influenced by engine operating systems, it was anticipated that the conductivity of deposits would also vary [36].

Additionally, according to Zerda, et. al. [37], a deposit’s internal microstructure may directly relate to its intractability and ease of removal. A more graphitic and condensed microstructure may be more impervious to oxidation and burn-off, and consequently more difficult to remove from the engine.

(1-1) Wall temperature effect

Depending on the temperature level at the location where deposits are formed, deposits will have different structures. Nagao, et. al. [38] stated that the deposit changes in quality according to the wall temperature. In the study, Nagao, et. al. [38] mentioned that at a high level of wall temperature (>550°C), the deposits are very thin, soft, dry and so removable that the gas flow existing in the combustion chamber can blow them off. In terms of quality, the deposits are mostly carbon. However, at a lower level temperature (<200°C), the deposits adhere to the wall and are moistened owing to the fuel. The deposits consist of fuel, adhesive and carbon.

Similarly with Lepperhoff, et. al. [26], the effect of different temperature ranges on deposit structures was described. However, the range of high level temperature was lower than that discussed by Nagao, et. al. [38]. At high temperature levels (>300°C) according to Lepperhoff, et. al. [26], different light deposit colors are visible. A very thin deposit layer is typical for this temperature range. However, at low temperature levels (<200°C), dark materials including black carbon, wet hydrocarbons and soot were observed in the study.

(1-2) Location of deposits

Zerda, et. al. [37] proved that the morphology of the deposits varies with their location inside the combustion chamber. The surface area and the total pore volume depend on the location of the deposit, whether removed from the cylinder head, the piston top, or the intake valve as shown in Figure 1-8.
The structure of the deposits removed from the combustion chamber’s cylinder heads is more porous than that of piston top deposits. Likewise, intake valve deposits were seen to be less porous than combustion chamber deposits. Pore size distribution of deposits for the cylinder head is the largest, followed by piston top and intake valve deposits.

![Graph showing pore size distribution](image)

**Figure 1-8** Comparison of pore size distribution of deposits generated by fuel without additives on different parts of an engine [37]

(1-3) Fuel component effect on deposit structure

Zerda, et. al. [37] also investigates the effect of additives on deposit structure and found that the additives change the distribution of pores in the deposits as shown in **Figure 1-9**. In the figure, additive concentrations for PEA-1 (polyether amine-based) and PBA-1 (polybutane amine-based) are the same. The study also found that increased concentration of additives results in reduced surface areas. This effect is accompanied by a small increase of the deposit mass. It is likely that the additives or their fragments are incorporated into the deposits by filling up and blocking access to some of the cavities. The surface area of the deposits decreases with increased concentration of the additives.

On the other hand, the study of carbonaceous deposits conducted by Zerda, et. al. [8] and Edwards, et. al. [39] concluded that fuels with higher aromatic contents yield more condensed deposits. Zerda, et. al. [8] add in the study that the fuel aromaticity increases the deposit structure which becomes more graphitic.
Figures 1-9 Comparison of pore size distribution of deposits generated by fuel with different additives at the same concentration [37]

(1-4) Deposit structure at different layers

Two distinct CCD morphologies were identified in a previous study when deposits were exposed to higher temperatures [7, 28, 40] as shown in Figure 1-10.

The first layer is the lower layer closer to the metal surface in which condensation of highly volatile compounds from fuel and oil takes place. The deposit in this layer has a “lacquer-type” structure and is very difficult to remove. This layer was also found to have a higher aliphatic portion than subsequent higher layers which were characterized by a coal-like structure. The deposits in this layer are more homogenous and maintain their cohesiveness.

The second layer which refers to the upper layer is composed of molecules with less bonding tendencies and which can be more easily removed. This layer is carbonaceous in character and has a soot-like chemical structure. In this layer, deposits were found to have an aromatic content similar to soot. In this deposit layer, more loose particles of different shapes with dull edges were also present. They were more disperse in structure and covered with very viscous liquid or
polymer.

**(2) Deposit properties**

The internal porosity of combustion chamber deposits may determine thermal conductivity, thermal diffusivity, and heat capacity, leading to the thermal insulation of the metal parts and heat storage [37].

Jonkers, et. al. [28] used a deposit conductivity probe installed in the cylinder head of a DI diesel engine to investigate deposit conductivity in a real engine. The study found that as deposit formation progressed, the deposit conductivity decreased as shown by the conductivity probe voltage drop in **Figure 1-11**. This was probably caused by an increase in the concentration of aliphatic groups and a decrease in polyaromatics in carbon black that led to the decrease of deposit conductivity. Soot is considered to be of a polyaromatic (graphitic) structure and thus highly conductive. Increased conductivity was observed during the initial start-up of the engine, possibly caused by the presence of aromatics. Thereafter, it is likely that aliphatic components from the oil contributed most to deposit formation as conductivity decreased. The probe voltage-drop profile changed around cylinder peak pressure with an inflection in the curve. It is believed that this change is also indicative of a change in deposit structure.

![Figure 1-11](#) Conductivity probe voltage drop for accelerated deposits [28]

Results of thermal diffusivity obtained from Guralp, et. al. [17] in **Figure 1-12** was calculated by using the relationship between local peak temperature phasing and combustion chamber deposit thickness combined with the formula of thermal

14
diffusivity. The result demonstrated a strong correlation between deposit thickness and the diffusivity of the combustion chamber deposit layer at two different locations of cylinder head surfaces for a homogenous charge compression ignition (HCCI) engine. Thicker layers of material have a lower effective thermal diffusivity. This is due to the fact that, as the deposit is forming, its morphology is constantly changing as well. The degree of porosity, the consistency, and the types of HC molecules that make up different layers of the total material are constantly changing.

Nishiwaki, et. al. [41] determined the thermal conductivity and diffusivity of deposits in SI and diesel engines based on one-dimensional unsteady conduction in a solid having constant thermal properties. For both engines, thermal conductivity was influenced by engine load. Additionally, for the SI engine, the properties were also influenced by the equivalence ratio and engine speed. In terms of thermal diffusivity, SI engine deposits also depend on the equivalence ratio, engine load and engine speed. However, for the diesel engine in the study, no clear factors effecting thermal diffusivity were determined.

![Figure 1-12](image)

**Figure 1-12** Plot of calculated effective thermal diffusivity as a function of CCD thickness at each heat flux probe location in the cylinder head [17]

Anderson, et. al. [42] claimed that the effective porosity of the material is a dominant characteristic which controls the rates of heat transfer at the surface, suggesting that conduction is indeed the major mode of heat transfer related to deposits. Tree, et. al. [43] extended this line of reasoning by claiming that the porous characteristics of the combustion chamber deposit layer actually interacted with fuel spray in a diesel engine, causing an increase in the duration of heat
Additionally, Woschni [44] suggested that the thermal storage capacity of deposits on the wall will cause the flame to burn closer to the present thermal boundary layer and actually increase the heat transfer to the wall.

1.3.3 Deposit mechanisms

Knowledge of how deposits are formed and what the influencing parameters are can be used to describe any deposit formation at different locations in engine’s combustion chambers. Furthermore, when the fundamental mechanisms of deposit formation in engine’s combustion chambers are clearly understood, engine deposits can be predicted which will help to improve engine durability.

Lepperhoff, et. al. [26] suggested the physical mechanisms of deposit which included the formation and removal mechanisms as illustrated in Figures 1-13 (A) and 1-13(B), respectively.

![Deposit formation and removal mechanisms](image)

**Figure 1-13** Deposit formation and removal mechanisms [26]

(1) Formation mechanisms

The mechanisms of deposit formation are described as a function of time and these mechanisms are influenced by physical conditions at the location of deposit formation such as temperatures, temperature gradients, conditions of flow concentrations and concentration gradients of depositable components. The depositable component can be divided into different groups: 1) Gaseous and high molecular liquid substances which follow the flow of the gas itself; and 2) particles
which cannot follow the gas flow direction.

(1-1) **Liquid film formation**

Liquid film formation can be caused by the condensation of heavy gaseous components [26] and fuel impingement on the wall surface. The reactivity and the evaporation behavior of the liquid components on the wall surface result in deposits.

In the case of condensation, this process is mainly influenced by the wall. The temperature gradient near the cooled wall caused thermal diffusion of heavy gaseous components. This effect resulted in an increased concentration of heavy gaseous components near the wall. These gaseous components are high boiling components, mostly hydrocarbons. The gaseous components condense and adsorb at the wall due to low wall temperatures. The deposit formation starts with this condensation of high boiling hydrocarbons at the wall.

Formation of fuel film through fuel impingement also contributes to deposit formation on the wall where the film also acts as a binder to the particles in the combustion chamber. The area directly exposed to spray impingement has high risk of obtaining a great amount of adhered deposits.

(1-2) **Sticking/ incorporation/ impaction of particles**

The temperature gradient near the cooled wall leads to high thermophoretic forces transporting the particles to the wall. Increasing temperature gradients lead to stronger thermophoresis. This effect causes increased particle concentration near a cold wall. The particles are deposited by sticking, incorporation and impaction. The sticking effect is caused by adhesive forces between the wall and particles. Incorporation is the attachment of the particles in a liquid surface layer. Impaction takes place by the phenomenon of thermophoresis.

No carbon particle can adhere to a dry, non-sticky wall. To build up deposits, a contact medium between the wall surface and particle is necessary. The contact medium is provided during the formation of liquid film on the wall surface. The deposits grow continuously by additional sticking and the incorporation of particles to the layer. With growing deposit thickness, the isolation effect takes place. This leads to an increase in surface temperature and low bonding forces restrict the deposition of more particles.
(1-3) Adsorption of gaseous component

The incorporation and impaction of particles probably develops the structure of deposits with high soot portions. The porosity of the deposit plays an important role in the adsorption of gaseous components. Gaseous components diffuse through the porous layer of the deposit and are adsorbed or condense in the layers of lower temperature. This results in an increase in the layer density supported by the pulsation of the gas flow.

(1-4) Reaction of hydrocarbons

Once the deposits are attached to the wall, an additional chemical reaction (oxidation, pyrolysis, dehydration, polymerization, etc) [26, 30] can take place. The chemical reactions are caused by the influence of temperature combined with the long residence time. If the wall temperature is relatively low, fuel accumulated on the wall can evaporate by the heat supplied by the surrounding gas of comparatively high temperature and the residual fuel is left on the surface as a lacquer-like substance [38].

(1-5) Compression of the layer

Compression during engine stroke might affect the deposit formation mechanism. The compression can change the structure of the deposit into a more compact structure. Further, the condition will effect the formation of the next layer. After a number of engine strokes, the deposit substance accumulates and then solidifies into a dry lump which is easily removed by some mechanical causes such as vibration, the impact of spray and drag force due to gas flow [38].

(2) Removal mechanisms

Lepperhoff, et. al. [26] suggested 6 types of removal mechanisms during deposit development in engines. The removal mechanisms are:

1) Oxidation of soot and hydrocarbon due to high gas and deposit temperature.
2) Evaporation of volatile fraction when temperature increases.
3) Desorption of gaseous components mainly caused by temperature increase.
4) Abrasion due to low adhesive force.
5) Break off, especially part of the deposit that has porous structure due to shearing stress.
6) Wash off, where flow of liquids brings away the deposit precursor probably having a potential for increasing the amount of deposit.

For these removal mechanisms, there is probably no sequence of mechanisms. The occurrence of each removal mechanism depends on engine operation and the condition in the combustion chamber. Deposited components are removed by physical, mechanical and chemical mechanisms.

Physical mechanisms include evaporation and desorption of volatile and gaseous components as well as mechanical wash off. Evaporation and desorption are initiated by an increase in temperature. For instance, this can happen at the deposit surface by thermal isolation effects of the deposits themselves.

Mechanical mechanisms include the abrasion of complete deposits or parts of them and the breaking off of porous deposits. Abrasion takes place when aerodynamic forces exceed bonding forces. The breaking off effect is initiated by a temperature change resulting in the extension of the wall and deposit layer. These unequal extensions lead to shearing stresses which enable the initiation of the breaking off mechanism.

Chemical mechanisms include the washing off of soluble deposit portions and the oxidized carbon and hydrocarbon deposits. Liquids such as condensate water and fuel wash off soluble deposits. To oxidize carbon and/or hydrocarbon deposits, an oxygen-rich atmosphere, certain temperatures and time are necessary. Oxidation starts at a temperature exceeding approximately 200°C for hydrocarbons and approximately 500°C for carbon. This high temperature can be caused by high gas temperatures or high deposit wall temperatures.

### 1.3.4 Factors of deposit formation

The formation of engine combustion deposits is a complex phenomenon which depends on various factors such as fuel, oil, additives, mixture preparation, combustion chamber design, wall temperature, gas flow conditions, gas concentration gradient near the wall, etc [17, 18, 26]. However, different engines and operating conditions are believed to result in different deposit formation as shown by the result in Table 1-2 obtained by Sevast’yanov [45] who investigated high-temperature deposits on pistons for different locomotive and marine diesel engines that used different grades of oils.
Table 1-2 Deposits formed on pistons for various diesel engines [45]

<table>
<thead>
<tr>
<th>Engine</th>
<th>Oil grade</th>
<th>Carbon deposits (g) formed on pistons after running locomotives 100,000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Piston head</td>
</tr>
<tr>
<td>2D100</td>
<td>M-12</td>
<td>0.7</td>
</tr>
<tr>
<td>2D100</td>
<td>M-12V</td>
<td>10.8</td>
</tr>
<tr>
<td>10D100</td>
<td>M-14V</td>
<td>12.6</td>
</tr>
<tr>
<td>11D45</td>
<td>M-14V</td>
<td>15.6</td>
</tr>
<tr>
<td>11D45</td>
<td>M-14Vts</td>
<td>14.2</td>
</tr>
</tbody>
</table>

From previous literature regarding deposit formation in an engine’s combustion chamber, factors such as liquid film formation, wall surface temperature, air/fuel ratio, engine operating conditions, and fuel and lubricant oil were widely investigated.

(1) Liquid film formation

Liquid film formation on wall surfaces in combustion chambers is one of the main causes of deposit formation. The liquid film that acts as a contact medium can be formed by fuel and/or lubricant oil whether through impingement, condensation or liquid flow on various engine parts in a combustion chamber.

Fuel film formation through spray impingement usually occurs in small, high speed engines during the injection period. For engines exposed to this type of fuel film formation, the amount of deposit accumulated and its thickness on the engine part surfaces are closely related to the wall surface temperature and also the fuel impingement area. The wall area that is directly exposed to spray impingement has a high tendency to obtain more deposit formation on the surface. As shown by the deposit conditions on a piston surface for single DI diesel engines in Figure 1-14, Yamada, et. al. [46] proved that the place where the fuel spray was expected to impinge had a greater amount of adhered deposits. As the engine running time increased, the amount of deposit accumulated at the area where the fuel spray impinged also increased.

Due to the high temperature and high pressure environment in a combustion chamber, the high boiling point hydrocarbons from fuel and lubricant oil vaporizes. Depending on the effectiveness of air/fuel mixing during the combustion process, part of these vapors are not burned, and these vapors that are in contact with wall surfaces having relatively lower temperatures condensed and formed liquid film on
the wall. Further, this liquid film was involved in various processes contributing to deposit formation. For fuel liquid film, the sources of condensed fuel can be leftover unburned fuel from incomplete combustion and extra fuel mass accumulated from direct injection spray impingement [17]. The boiling point of the fuel was a good indicator for its tendency to result in deposit formation through condensation. Higher boiling point fuels have a greater chance of condensation, leading to greater rates of deposit formation than lower boiling point fuels.

![Figure 1-14 Deposit formation on the piston surface after 285 min. after engine start [46]](image)

The intake valve and injector nozzle holes are the common parts of an engine that involve liquid flow. The tendency of deposit precursors to remain on the wall depends on the wall temperature and fuel distillation properties. The deposit precursors disperse in fuel that remains on the wall. After a time, the fuel will evaporate and leaves deposit precursors on the wall. Kinoshita, et. al. [47] investigated the factors of nozzle deposit formation through an injector bench test and engine dynamometer test, and mentioned the significant effect of the distillation temperature of fuel. In the study, it was found that when the wall temperature is lower than T90 distillation temperature of the fuel, where most of the fuel remains in a liquid state, the deposit precursor was wash away by the next fuel flow. Due to the wash off process, less deposit remained on the wall for lower temperatures. However, when the wall temperature is higher than T90,
most of fuel evaporates and the deposit precursors cohere to the wall.

The result obtained by Kinoshita, et. al. [47] is shown in Figure 1-15. The reduction of fuel flow rate in the figure is dependent on the formation of deposits in the nozzle holes. More deposit formation caused more reduction of fuel flow rate. Thus, the nozzle temperature close to T90 temperature obtained a greater reduction of fuel flow rate due to more deposit formation. From this evidence, the effect of wall temperature for deposit formation involved in liquid flow was different than the effect of wall temperature on deposit formation through spray impingement and condensation.

![Figure 1-15](image)

**Figure 1-15** Relation between nozzle temperature and reduction of fuel flow rate in an injector [47]

Lepperhoff, et. al. [26] investigated the liquid flow effect on deposit formation in a cooled pipe with a diesel exhaust gas stream and used oil as a liquid. At places with a smaller liquid flow, the incorporation of particles causing an increase in viscosity that leads to a slowing down of the liquid flow. Here the liquid went to a sticky layer with the effect of a higher collection and incorporation of particles. The higher the rate of incorporated particles, condensed depositable components and absorbed depositable components, the higher the build up of deposits. A wall covered with liquid with a high liquid flow sufficient to produce a continuous wash off of all particles of deposit, can reduce deposit formation on the wall. These explanations can be applied to deposit formation on the intake valve, on the injector tip and in the injector nozzle. The effect of liquid flow on deposit formation is shown in Figure 1-16.
The continuous formation of liquid film on a wall surface further develops the wall wetting condition. Excessive wall wetting seemed to be the reason for deposit formation. This was proved by the high-boiling fractions of fuel that was found in the deposits as mentioned by Eilts [25] in his theoretical work. Furthermore, Guralp, et. al. [17] observed that the thickest deposit layer is found on the areas which have relatively plenty of fuel in liquid form. The deposits probably formed mainly from liquid hydrocarbon that had been deposited on the wall in the liquid state and evaporated incompletely. High temperature in the combustion chamber caused the volatile and non-volatile components of the liquid hydrocarbon to be involved in further reactions inside the cylinder. At the same time, the carbonizing effect is significant. The percentage of non-volatile substances (e.g., carbon, metallic salts) increases while that of volatile substances decreased. This led to the formation of deposits on the wall surface in a combustion chamber.

As a conclusion from the information on liquid film formation, the amount of deposits accumulated during engine operation are different at different parts and locations in the combustion chamber due to different mechanisms of liquid film formation and wall surface temperature.

(2) Wall surface temperature

Wall temperature effect is the most important factor for deposit formation. Related to this statement, Ye, et. al. [18] mentioned that combustion flame temperature and cylinder surface temperature are major factors in cylinder deposit
formation. The high temperature of the flame and combustion chamber causes severe carbonization of deposits. Different parts in the combustion chamber have different wall temperature regimes and differing exposures to depositable components. In an investigation that conducted by Zerda, et. al. [37], deposits that formed on those parts have likewise differing chemical and physical properties.

In general, the highest heat flux occurs in the center of the cylinder head and near the exhaust valve seat, and at the center of the piston crown [48]. The greater amount of deposits usually accumulated on the piston which is the most highly stressed part [22] and also on the area closer to the fuel injection nozzle [46]. The highest thickness of deposit layer was found on the edge of the piston bowl where the average temperatures are relatively lower. Fewer deposits were found on the intake and exhaust valves due to their higher surface temperature [17, 46]. The lower deposit mass with rising piston temperature is evident as mentioned by Eilts [25] and shown in Figure 1-17 for the points collected in band a-a. Various points in the figure show different engine operating conditions. For each point, one different parameter was changed to observe the difference in deposit accumulation. The results shown in the figure emphasize the significance of wall surface temperature in determining the amount of deposits adhered on the wall surface in a combustion chamber.

![Figure 1-17 Correlation between deposit mass and piston temperature [25]](image)

The combination of low wall temperature and unburned fuel cause greater deposit formation in a combustion chamber. Hence, the area where fuel spray was expected to be impinged obtained a greater amount of adhered deposits as
mentioned before by Yamada, et. al. [46]. Eilts [25] also showed that there are correlations among deposit mass with piston temperature, fuel temperature and, the concentration on the jet centerline at the point of impact.

(3) Air/fuel ratio

The air/fuel (A/F) ratio is another major factor for deposits formation. Ye, et. al. [18] investigated deposit accumulation in engines by using the SI engine bench test under various A/F ratios. The study found that at high speeds and in the heavy-load region, the amount of deposit accumulated on the sample plug installed in the cylinder head of the engine decreased when the A/F ratio mixture changed from a rich condition to the stoichiometric A/F ratio as shown in Figure 1-18. The amount of deposit starts to increase again when the A/F mixture reaches a much leaner condition. As explained by Ye, et. al. [18], the rich mixture has a low oxygen concentration leading to incomplete combustion. Halfway products from the incomplete combustion tend to accumulate on the cylinder wall, piston surface and intake and exhaust valves. Due to the high temperature of the flame and combustion chamber, the carbonizing effect is remarkable where a large amount of combustion deposit accumulated on the wall surface. Under rich conditions, the combustion deposit on the chamber wall grows with an increase of engine power.

![Figure 1-18 A/F ratio effects on deposits](image)

**Figure 1-18** A/F ratio effects on deposits [18]
When the A/F ratio continues to increase, an excessively lean mixture was present. Halfway products cannot react fully because of the low flame and reaction temperature. Hence, some significant amount of reaction products accumulates on the combustion chamber surface; other amounts are emitted out of the cylinder into the exhaust system. As a result, the amount of deposit accumulated on the sample plug increased.

A similar result was obtained by Steve Cheng [49] who investigated the impact of engine operating conditions on the formation of combustion chamber deposits. He found that the minimum amount of toluene-derived deposit was obtained at a near stoichiometric fuel-air equivalence ratio as shown in Figure 1-19. Both leaner and richer conditions in the study obtained an increase in the amount of deposit on the combustion chamber’s wall.

![Figure 1-19 Effect of fuel-air equivalence ratio on deposits at four sampling sites](image)

(4) Engine operating conditions

Various studies have been conducted on the effect of various operating conditions on deposit formation in engines. Nagao, et. al. [38] found that, deposit accumulation is not effected by decreasing engine speed from 1200 rpm to 600 rpm in spite of doubled fuel quantity per unit time as shown in Figure 1-20. In addition, Diaby, et. al. [30] suggested that the down-sizing and the extreme conditions of the engine operation (e.g. operational temperature and pressure of the combustion chamber, the oil sump, or the cylinder liner temperature) could accelerate the process of deposit formation in the engines. Ye, et. al. [18] discussed the deposit effect especially on HC emissions at different cylinder
pressures, where, in general, the effect of deposits under a low cylinder pressure condition is greater than under a high cylinder pressure condition. A small compression ratio is appropriate to minimize the temperature-induced problems and to decrease deposit formation.

Lepperhoff, et. al. [26] mentioned that new deposit formation problems occur in new and existing engines as a result of changes in operating conditions due to modifications in engine design and/or the operating combustion processes. For example, injection nozzles in DI diesel engines can be fouled, even at low load operation over a long distance. A high pressure fuel system and narrow spray holes that lead to increased temperature in the area of the injector tip might be the reason. This statement aligns with the conclusion made by Eilts [25] where by modification of the injection system, such as reducing the diameter of the nozzle holes and high opening pressure, causes no improvement in reducing deposit formation.

![Figure 1-20 Influence of engine speed on deposit formation [38]](image)

(5) **Fuel and lubricant oil**

Mayo, et. al. [50] investigated the contribution of soluble gum to hard deposit formation on hot engine parts. The gum formation always exists before deposits and usually in greater quantity, where aromatic hydrocarbon is an important cause of the gum formation. The formation of deposit precursors depends on the aromaticity and solvent properties of fuel and gum formation. Many studies have proved that deposit formation increases with the increasing unsaturated bonds in the fuel molecular structure as mentioned by Kalam, et. al. [5].

Most gum and deposit formation is associated with oxidation by oxygen.
Hazlett, et. al. [51] investigated the oxidation of n-dodecane over a stainless steel surface and concluded that deposit formation is closely associated with pyrolysis of hydroperoxides. Kim, et. al. [52] investigated the effect of surface temperature and oxidation on deposit formation as shown in Figure 1-21 and concluded that the deposit formation increases rapidly for the case of high oxidation oil (high value of DIR_{oxidation}) and high surface temperature.

Konno, et. al. [11] mentioned that, the factors effecting deposit formation are most likely the distillation property, particulate forming propensity, and the value of viscosity. The distillation property is a dominant factor effecting deposit formation. The deposit formation increases with the increasing boiling point of a hydrocarbon fuel [5, 38].

Ullmann, et. al. [27] investigated the interactions of certain diesel fuel additives on deposit formation. The data obtained in the study suggest that when additives are present alone, they do not seem to be able to generate any degradation product and hence no deposit formation occurred. However, combinations of certain additives can cause the formation of deposits. For example, the combinations of typical diesel detergents and di-fatty acids seem to be the most critical and can form gum-like polymeric deposits. This is exacerbated when formic acid is present.

![Figure 1-21](image)

**Figure 1-21** Effect of surface temperature and oxidation on deposit formation in gasoline engine oils [52]

The engine testing for diesel injector deposits carried out by Leedham, et. al. [33] showed that base fuel did not have significant level of deposits. But, in the presence of trace amount of Zinc, a substantial level of deposits is generated. Thus, fuel quality has significant effect on deposit formation.
For gasoline engine, Ansomboon, et. al. [53] investigated the effect of olefin and additive content in fuel on the amount of deposits accumulated for the intake valve and combustion chamber by using a six-cylinder SI engine. The study found that by increasing the amount of olefin in the fuel, the tendency of deposit formation on the intake valve and combustion chamber increased. However, when adding detergent additives in the base fuel, the intake valve deposit decreased with the dosage of the detergent additives, while the combustion chamber deposit increased.

1.3.5 Engine problems due to deposits

(1) Heat transfer in the combustion chamber

The surface condition of the combustion chamber wall is considered a rate control factor for deposit formation. Unburned fuels that adhere on the combustion chamber surface are involved in heating and vaporization processes that form deposits on its surface.

The deposit layer will act as a thermal insulator where it affects heat release in the combustion chamber. As shown in Figure 1-22, Yamada, et. al. [46] and Ishii, et. al. [54] found that the variation of instantaneous surface temperature and heat flux was caused by the amount of deposit adhered on a wall surface. The greater amount of deposits produced more variation of the surface temperature and heat flux. Low thermal conductivity of deposits cause conduction rate reduction and retards the capability of heat release from the combustion chamber. Due to the thermal isolation effect of the deposit, the surface temperature of deposits ($T_{\text{Deposit}}$) is higher than that of the clean wall ($T_{\text{Wall}}$) as illustrated in Figure 1-23. The amount of heat release and temperature difference between $T_{\text{Deposit}}$ and $T_{\text{Wall}}$ depend on the thermal properties of the deposits. The low thermal conductivity of the deposit adhered on the wall surface of the combustion chamber is caused by porous structure and non-volatile matter like ash in the deposits [48].

The increased surface temperature of the deposits leads to a reduced temperature gradient in the gas [26]. As a result, an overheating of the cylinder wall occurs in the combustion chamber, which can further cause engine knock and fuel degradation which will cause more deposits, increase in combustion flame and exhaust gas temperature as mentioned by Ye, et. al. [18].
Figure 1-22 Effect of deposits on instantaneous surface temperature and instantaneous heat flux (1200 rpm, full load) [54]

Figure 1-23 Heat transfer effect due to deposit layer

(2) Engine performance

(2-1) Fuel atomization

Fuel injector nozzles are exposed to high temperature combustion gases and soot in the combustion chamber. In such an environment, the deposits that form on the injector tip and in injector holes are able to change the spray shape [55] and fuel flow rate [47], respectively. Furthermore, the deposit can also slow down the injector dynamics and delay the closing of the needle due to deposit formation in
the fuel injector. These problems have maximum effect at short injection times. Furthermore, as mentioned by Ullmann, et. al. [27], at full load and high injection pressure, internal injector deposits can reduce the injection amount resulting in power loss.

(2-2) Combustion event

Combustion chamber deposits (CCD) that form on both piston tops and cylinder heads could adversely affect the operation of an engine. The CCDs affect ignition not only due to the variations in heat transfer during intake/compression, but also produce an additional strong effect on bulk burning due to altered near-wall boundary conditions [17]. A fresh mixture is also heated by the engine deposit during the intake and compression strokes [18]. Such effects can lead to various forms of abnormal combustion such as the existence of hot spots that cause uncontrolled surface ignition which leads to knocking [37]. Another form of abnormal combustion can result from heat regeneration and thermal insulation effects leading to auto-ignition knock that results in octane requirement increase (ORI) [48] and loss of engine power through spark advance reduction [37].

Deposit formation at certain parts in the combustion chamber will also disturb the combustion process. Tondelli, et. al. [56] investigated the effect of deposits that are accumulated at the squish area in an engine cylinder which involves approximately 25% of the overall deposit accumulated in the study. The deposits disturb the turbulence flows that are intended to improve the air fuel mixture in the cylinder. Thus, the air-fuel mixture obtained due to the deposits in the area was poorer compared to the condition of the area without deposits. Figure 1-24 illustrates the effect of deposits in the squish area.
A typical effect caused by the deposits in diesel engine is diesel knock, where the rate of pressure rise is high enough to cause noise or excessive vibration in engine structure. The tendency of diesel knock increases rapidly with deposit accumulation [6]. The knock increase is apparently caused by the fact that, as the deposits build up, both the effective compression ratio and effective temperature of the inner wall surface increase [6]. The compression ratio increases because the deposits bulk volume reduces the volume of the combustion chamber at the top dead center (TDC) position.

The compression ratio was found to be effected by engine deposits where the ratio is increased until the deposit accumulation reaches a steady state as does the cylinder wall temperature [18]. The formation of deposits in the combustion chamber reduces the clearance volume, and, as a result, it increases the compression ratio of the engine. However, different types of engine probably will have different degrees of a deposit’s effect on engine compression ratio. As the result obtained by Guralp, et. al. [17] for a homogenous charge compression ignition (HCCI) engine, even the most extensive degree of deposit coverage in the chamber would only increase the compression ratio a negligible amount.
(3) Engine emissions

In terms of pollution, obviously fuel deposits, such as on the piston top and cylinder head [57] have a negative contribution to the emission of hydrocarbons (HC) and ash in the environment. As deposit formation increases in the combustion chamber, hydrocarbon (HC) emissions increase as well. It was believed that adsorption and desorption of hydrocarbons by the deposits was the mechanism that caused this undesirable increase in emission [48]. As mentioned by Eilts [25], high HC level in combustion emissions had been shown to be caused by excessive wall wetting and it seemed probably that the same mechanism was the reason for deposition development. Eckhause, et. al. [58] mentioned that the wet condition is significant because it is the appropriate surface condition of the diesel combustion chamber wall. During the wet surface condition, lighter molecular weight compounds will evaporate and the heavier molecular weight compounds will remain on the surface and turn into deposits. Figure 1-25 shows the increase of HC emission with deposit mass accumulated as mentioned by Eilts [25] in his study. The points indicated in the figure are for different combinations of engine operation parameters. Tondelli, et. al. [56] also obtained the same conclusion. In the study, HC emissions between combustion chamber with and without deposits were compared. The condition with deposits in the combustion chamber resulted in more HC emission.

However, there is some uncertainty as to the exact effect of CCD on emission. In some cases [59], the HC emissions increase dramatically due to high CCD accumulation, while in other cases [60, 61], the CCD formation has no effect on HC emissions. This uncertainty stems from the fact that CCD can act either as a HC increasing agent by absorbing and desorbing unburned fuel [57]. The effects of the CCD on the HC emissions are dependent on which of these mechanisms is dominant for a given engine and operating condition [7].

It has also been observed that the accumulation of combustion chamber deposits may lead to an increase in oxides of nitrogen (NOx) [61, 62]. Increased deposits have led to an increase in NOx due to their insulating effects that increased the cylinder temperatures [28].

In addition, as mentioned by Ra, et. al. [32], soot emissions are integrally related to soot deposit build-up on engine surfaces since part of the soot generated during the combustion process in the cylinder is deposited on the combustion chamber surfaces, which are protected from oxidation. Deposit formation could have some degree of effect on the increment of soot emissions from an engine.
Engine damage

Deposit formation also causes physical damage to the engine parts in the combustion chamber. Continued operation with CCDs has been known to result in physical damage due to piston and cylinder head interference, often occurring during the cold start-up of engines [63]. In diesel engines, bore polishing leads to engine damage. However, deposit formation at the valve seats lead to damage in spark-ignition engines [26]. As the engines age, engine component wear and deteriorate, causing more oil introduction into the combustion chambers. As a consequence of these phenomena, more deposits due to oil and oil additives can form [7]. Thus, more severe damage might occur.

1.3.6 Deposit preventive measures

Deposit formations in engines depend on many interrelated factors. Thus, there is no specific solution for deposit reduction in an engine. However, many studies suggest general preventive measures for various engine types and operating conditions. The preventive measures suggested here are from various considerations and were suggested according to their investigation on deposits in real engines.

(1) Engine parameters

Eilts [25] presented measurements of deposit formation in a direct injection
diesel engine during low load operation and found that the effective reduction of deposit formation is possible by increasing the compression ratio, the charge air and exhaust gas pressure as shown in Figures 1-26(A) and 1-26(B) for various parts of a combustion chamber. A higher load operation, e.g. by cylinder cutout and advancing fuel injection timing, demonstrates a positive trend in reducing deposit formation as shown in Figure 1-26(C).

![Figure 1-26](image)

(A) Compression ratio  (B) Charge air pressure  (C) Load

**Figure 1-26** Variation of compression ratio, charge air pressure and load [25]

In some cases, in order to combat deposit accumulation, de-coking procedures have been adopted [64]. This type of procedure entails periodic operation of a diesel engine at high loads in order to achieve high enough cylinder temperature to oxidize the deposits [28]. Ye, et. al. [18] suggested in order to minimize the deposit accumulation, it is good to minimize the portion of partially burned mixtures and halfway products by adjusting the value of the A/F ratio.

In terms of engine damage, Muzikus, et. al. [22] investigated the standard allowable limit for carbon deposit formation by analyzing the carbon deposit rating relationship with actual deposit formation on different parts of piston components in diesel engines in order to minimize the damage caused by deposits.

(2) Engine design

By modifying the design of an engine, deposit problems can be controlled but redesign can lead to new deposit characteristics [7]. Ye, et. al. [18] suggested that
deposit formation can be reduced by minimizing the surface-to-volume ratio in order to reduce the surface area subject to engine deposits. As suggested by Jonkers, et. al. [28], a “fire” ring may be fitted into the cylinder liner in order to scrape off fuel and lubricant debris around the piston crown. Nagao, et. al. [38] recommended in terms of combustion chamber design, it is important to promote mixing of fuel and air, thereby removing an unusually rich mixture as well as to avoid direct impingement of fuel spray onto the wall. As a result, deposit formation can be reduced. Caceres, et. al. [7] emphasized the necessity to increase the durability of the engine components so as to reduce the oil introduction into the engine cylinder in order to minimize the CCD formation that was caused by lubricant oil.

(3) Deposit mechanism considerations

Some studies suggested preventive measures according to the deposit formation mechanism. Ye, et. al. [18] suggested by maximizing the ratio of the deposit releasing rate (evaporation, reaction) to the condensing rate among the engine deposits (e.g., high volatility), deposit formation can be reduced. If the rate of deposits being depleted is faster than that being created, deposits diminish gradually. In order to prevent carbon deposits in the combustion chamber of a diesel engine, Nagao, et. al. [38] recommended avoiding direct impingement of fuel on the wall of combustion chamber according to the result obtained in Figure 1-27.

**Figure 1-27** Relationship between wall temperature $T_W$ and maximum and minimum weights of deposits [38]
Lepperhoff, et al. [26] suggested that in order to prevent deposit formation that form due to liquid flow (such as on intake valves, injector tips and injector holes), the wall surface must be covered by the liquid and the liquid flow must be high enough to continuously wash off all particles. On the wall surface in a combustion chamber, when initial deposits accumulate, deposit growth runs up until removal and formation mechanisms are in equilibrium. Therefore, deposits can be prevented completely only by avoiding the induction phase of deposit formation mechanisms. This can be achieved either by washing off the depositable components or by avoiding the formation of a liquid surface layer.

(4) Wall temperature control

In order to suppress the formation of carbon deposits, Nagao, et al. [38] proposed raising as high as possible the temperature of the wall where the fuel spray impinges, to minimize deposit formation, as shown in Figure 1-27. This is an ideal condition for deposit elimination. However, this condition could not be expected in large size engines, because the temperature of the piston was limited below 330°C to 350°C on account of thermal load. The Nagao, et al. [38] study also found that when the impingement of the spray on the wall is avoided, the growth of deposits is easily removed when the wall temperature is kept higher than 200°C.

Kinoshita, et al. [47] believed that in order to suppress deposits in the nozzle holes, nozzle temperature need to be lower than the T90 temperature of the fuel. As such, the residual fuel in the nozzle hole is kept in a liquid state wherein also the deposit precursor was washed away easily by the fuel injection. As a result, deposit formation was restrained in the nozzle hole.

(5) Fuel and lubricant formulation

Additives can be used to suppress the formation of deposits in engines. The utilization of fuel additives can also prevent deposit formation in an engine, where the additives are mainly used to prevent the induction phase of deposit formation. Thus, it can help to reduce deposit problems drastically.

However, all the benefits provided by the additives can only be maintained if the correct combinations are used. As found by Ullmann, et al. [27], it is clearly indicated that the use of lubricity additive chemistries that do not further react with other compounds present in the fuel represents the best way to avoid the new type
of injector deposits. Where possible, replacing acidic based additives by neutral chemistries would help to avoid these types of deposits whilst maintaining the protection provided by diesel detergents.

For instance, the change from leaded gasoline to unleaded and the addition of deposit control additives have helped to control manifold and intake deposits [63]. Moreover, as mentioned by Jonkers, et. al. [28], improved lubricating oil and fuel formulations have helped to control deposit formation for both spark ignition and diesel engines. A diesel engine study [65] confirmed the need for formulating oil with appropriate additives since the lubricating oil is the major source of piston deposits. Fuels with higher proportions of aromatic content have been known to cause delayed ignition, which in turn promotes cylinder wall hydrocarbon leading to deposits. The effects of delayed ignition have been reduced in some cases by the use of combustion catalysts. By developing special fuel and/or lubricant compositions and/or additives, deposit problems at various locations can be controlled [26].

1.4 Purpose of this study

1.4.1 Overview of recent studies

In the literature, various types of bio-diesel fuel effects on engine emission and performance have been widely discussed. Bio-diesel fuel properties such as density, viscosity, distillation properties and chemical properties are among the properties that are responsible for causing different behaviors and effects that occurred when utilizing bio-diesel and bio-blended diesel fuel in an engine compared to typical diesel fuel. By referring to the properties, these types of fuel will have higher tendencies toward deposit formation in an engine compared to diesel fuel. However, the aspects of deposit formation when using bio-diesel fuel are not well known or understood.

Investigations on deposits in engines for gasoline and diesel fuels were conducted more than 40 years ago. Many investigations have been conducted in order to understand the deposit effects on engines and how these deposits develop in engines. It was found that deposits in combustion chambers can form through three different types of formation process: (1) through condensation of unburned gases on cooler walls in combustion chambers; (2) through impingement of unburned fuel droplets on walls; and, (3) through fuel flow on walls such as on intake valves, on injector tips and in injector holes.
Generally, there are three main investigations on deposits which are now still continuing due to various types of engines that are available and also due to new developments in engine technology. The investigations cover (1) the effects of deposits on engines; (2) the factors that cause the deposit formation; and, (3) the investigation of deposit properties. The effects of deposits on engines are include emissions, heat loss, engine performance and engine damage. However, the factors effecting deposit formation, such as fuel and oil, engine operating conditions, wall temperatures, and air/fuel ratios, are still being investigated for various types of engines. Deposit properties were also investigated in order to learn more about thermal properties and its structures. This last investigation is related to and effects the first two investigations mentioned above. The porosity of deposits is closely related to emissions and heat loss. Further, deposit structure and composition determine the wear that causes engine damage. As a result of these studies, deposit mechanisms and deposit formation preventive measures in engines have been suggested.

Most deposit research available in the literature was conducted by using real engine tests. Real engine test can be categorized into two types. Those using engine bench tests and those using vehicle tests. Both tests require long periods and traveling long distances, respectively. Some deposit investigations for engine bench tests required up to approximately 200 hours of engine operation \[7, 103, 104\]. Others, such as Hutchings, et. al. [105] conduct investigations on deposit control by using a new lower-emission engine test with 360 hours of engine operation. In terms of deposit investigation through vehicle tests, long distance travel is required to obtain a significant amount of deposit and effects for certain investigation. Tarkowski, et. al. [106] conducted an investigation to determine the influence of fuel oils on the deposit composition in a diesel engine combustion chamber, where the investigation required 70,000 km of travel distance. Due to long periods and long travel distance, both types of test involved high operating costs and were exposed to engine damage during the deposition test.

The deposit formation in an engine appears to depend on a combination of different parameters, such as fuel, surface material, temperature, pressure, combustion chamber environment, etc. However, wall temperature is one of the most important parameters that effect the deposit formation. Jonkers, et. al. [28] mentioned the effect of different operating parameters on deposit formation such as engine load, power output, surface temperature, coolant temperature and injection timing. No specific conclusion can be made for each type of parameter.
in explaining the deposit formation. For each parameter, deposits could be increased or decreased depending on the interaction between other parameters of the engine in effecting the deposit formation, where the interaction might be different for different types of engines. Due to the many factors and parameters effecting the deposit formation in an engine, it is considered a complex process. Because deposit formation is caused by such complicated phenomena, there are few cases of research available on the detail mechanisms involved.

In order to understand the mechanism of engine deposit formation and to find more effective solutions for deposit reduction, both real engine and fundamental studies on engine deposits are significant. Fundamental studies on deposit formation are very important. Extensive studies have been done on the evaporation of fuel, especially single and bi-component fuels [66-72] and also on actual multi-component fuels [73, 74] that can serve as part of the fundamental knowledge in deposit formation.

Actually, in discussing deposit formation, the few aspects involved include the vaporization process, heating process, deposit formation and chemical reaction process (thermal decomposition, polymerization, oxidation, etc). Among these aspects, only vaporization is widely discussed in the literature in terms of theory, modeling and experimental results [75-79]. To our knowledge, the other aspects mentioned before have not been discussed in detail.

1.4.2 The importance of deposit investigation

In the literature, there is still a lack of information on detailed research on deposit formation. The formation of deposits in combustion chamber was not well known and needs further investigation. This is a significant requirement in order to solve the problems involved with deposits as mentioned above. A clearer understanding of deposit formation might contribute to reducing deposit formation in engines. Thus, any problem related to deposit formation may be solved as well.

The evaporation and deposition of fuels are important probably before and after combustion, where the temperature at that condition is relatively low. At that condition, fuels remain that adhere on the combustion chamber surface which are involved in the heating and evaporating process that form deposits on its surface. As mentioned by Eilts [25], deposits were probably formed mainly from fuel that had been deposited on the wall in liquid state and evaporated incompletely. However, before considering deposit formation in detail, the vaporization of
volatile components is important to understand. This process determines the amount of fuel remaining which contributes to deposit formation.

Due to the difficulties of applying engine deposition tests such as long running time, parameter settings and the complex phenomena of deposit formation, simpler test procedures that can produce similar results in terms of deposit formation and development are needed. Furthermore, it is difficult to observe the formation mechanism of deposits and also its development in a real engine. During engine operation, great numbers of fuel droplets are also involved in the combustion chamber. Hence, being able to understand single droplet deposition will contribute significantly to understanding part of the actual process of deposit formation in engines. Therefore, we need an accelerated deposition test to evaluate and to analyze engine deposition.

1.4.3 Objective of this study

The aims of this study are first to clarify fuel deposition in an engine by using a simplified method known as the hot surface deposition test (HSDT). The second aim is to simulate and investigate deposit formation and development for diesel fuels and bio-diesel fuels on the wall of a combustion chamber caused by unburned fuel spray impingement. HSDT is an acceleration experiment instead of the engine deposition test (EDT), and is also considered an initial research step in developing simplified methods to investigate engine deposits for various types of fuel.

The simplified method was proposed in order to avoid the complexity of deposition tests in a real engine. This method becomes more significant when employed with the utilization of bio-diesel fuel, where these types of fuel have higher tendencies to produce more deposits in engines compared to typical diesel fuel. Through this simplified method, engine operation costs due to long operation can be avoided. Furthermore, engine damage due to uncertainties of deposit accumulation when different types of bio-diesel fuel are used can also be avoided.

This study focuses on continuous droplet impingement and evaporation. Different droplet impact conditions involved during deposit formation for continuous droplet impingement will be discussed in a later chapter. The availability of HSDT was first discussed with the comparison of depositions in an engine. Then, the deposition tendencies of diesel fuels, bio-diesel fuels and bio-blended diesel fuels were investigated by using this proposed method. In
explaining deposit formation, the evaporation characteristics of fuels and deposit surface temperatures were analyzed. These contribute significantly to increased understanding of deposits in engines. Through this study, the deposit formations for continuous droplet impingements at various hot surface temperatures were also investigated. Additionally, the hot surface temperature region that showed potential in reducing deposit formation was identified. Deposition characteristics, deposit formation mechanisms and factors influencing deposit formation for diesel fuels, bio-diesel fuels and bio-blended diesel fuels can be understood. Further, fuels having greater potential in reducing deposit formation tendencies can also be identified.

The combustion process in real engines involved heating, evaporating and burning of fuels. However, in the HSDT study, the process was limited to the heating and evaporation of fuels due to the test being conducted under atmospheric conditions with no combustion. Thus, deposit formation on a hot wall surface refers to the deposition that was caused by unburned fuel impingement. Parts of the physical mechanism suggested by Lepperhoff, et. al. [26] such as incorporation/impaction of particles and adsorption of gaseous components are neglected. However, other parts, such as thin film formation and reaction of hydrocarbons, are involved in our present study.

By conducting this study, basic knowledge of deposit formation and development can be understood. Furthermore, this research may help in understanding the more complex behaviour of deposit formation in real engines.
Chapter 2

Methodology of deposition research

2.1 Introduction of the deposition test

In real engines, a great number of fuel droplets are involved during atomization. The droplets evaporate and burn in the combustion chamber space. However, some of the droplets find their way to impinge the wall surface in the combustion chamber as illustrated in Figure 2-1. The interaction between fuel spray and a surface within an engine lead to the deposition of liquid fuel films [80]. This liquid film formation is one of the factors that caused deposit formation on the wall surface in the combustion chamber.

Figure 2-1 Deposit formation mechanism in an engine
In some cases for diesel engines, fuel spray impingement on a hot wall surface in a combustion chamber cannot be avoided. For example, in a small bore DI diesel engine, at high load engine operation, more than 50 percent of the fuel impinged upon the piston bowl as observed by Werlberger and Cartellieri [81]. The tendencies of fuel spray impingement with a hot wall surface in an engine increase due to following reasons:

1) Higher injection pressure that increased spray penetration and also when the spray impingement was used as a design consideration to promote spray atomization [58].
2) Engine operation with longer ignition delay compared to the injection period [6].
3) Engines that have a short distance between the injection nozzle and the piston head such as for small and high speed engines [82].
4) Unburned fuel droplets resulting from incomplete combustion (such as for bio-diesel fuels) [83].

As fuel spray impinges on the wall surface in an engine, liquid fuel film forms on the surface. The amount of fuel film that adhered on the wall depends on the wall surface temperature. The wall temperature will determine the amount of non-volatile or heavy molecular weight fuel components that remains on the wall and also the droplet-surface interaction during spray impingement. Probably, less liquid film adhered on the wall for high surface temperatures and also when the interaction is within the transition boiling regime. Within this regime, more droplets will bounce as secondary droplets to be impinged on the other surface areas in the combustion chamber or emitted from the engine during the exhaust stroke. The liquid fuel film that adhered and remained on the wall surface will further experience physical (evaporation, impaction of particle, etc.) and chemical (thermal decomposition, polymerization, etc.) processes due to the hot wall surface temperature. This results in deposit development on the wall surface in the combustion chamber as illustrated in Figure 2-1.

During the combustion process, the deposit formation, especially carbonaceous deposit formation, is more severe due to high temperature gases and flames that increase the carbonization process. Furthermore, the attachment of soot particles also occurs during the process. In a real engine, high gas temperature and flames caused part of the deposits on the wall surface to burn and oxidize rapidly, resulting in deposit reduction. The reduction of deposits in an engine can also be
caused by other factors, such as gas flow, piston movement and vibration, where part of the deposit is removed physically and emitted from the engine during the exhaust stroke of the engine. The next spray impingement will impinge on the deposit layer surface that formed from the previous impingement. The deposit formation processes as mentioned above repeat until the end of engine operation. During engine operation, the deposit layers also piled-up and covered the wall surface of the combustion chamber. However, in a real engine, after a certain period of time, the amount of deposit accumulated on the surface will stabilize, where the rate of deposit formation and the rate of deposit removal reach an equilibrium state.

Deposit formation in an engine is a complex phenomenon and it is difficult to observe deposit development and its mechanisms in a real engine. Thus, a simplified method known as a hot surface deposition test (HSDT) was proposed in this study. The basic concept of this simplified method is the repetition of fuel droplets on a hot surface resulting in the piled-up deposit process on the wall surface. The repetition and the piled-up deposit processes on a hot wall surface are shown in Figure 2-2.

In the figure, a fuel droplet is released from the needle tip to be impinged on the hot wall surface to form fuel film. Volatile components of the fuel film will vaporize and leave behind non-volatile fuel components on the hot wall surface. Further, these non-volatile fuel components will slowly oxidize and transform into carbonaceous deposits. Similar to an engine, the amount of non-volatile fuel remaining on the hot wall surface in this simplified method also depends on the wall surface temperature. The higher surface temperature will result in less non-volatile fuel remaining and also less deposits.

The next droplet will be impinged on the surface at a constant impingement interval at the same impingement point. However, the surface may have changed from the previous impingement due to the formation of a deposit layer. Again, volatile fuel components will vaporize and leave behind non-volatile fuel components that further will change into deposits that result in a new deposit layer formation at the impingement point. The amount of deposit is increased due to the addition of non-volatile fuel components that remained after the impingement. For every repetition, the amount of deposit accumulated also increases. The process of droplets impinging on the surface occurs repeatedly. The addition of non-volatile fuel components remaining on the wall surface and the piled-up deposit process keeps repeating throughout the experiment.
The repetition and the piled-up deposit processes in this simplified method are similar to the deposition process due to spray impingement on wall surfaces in an engine as described previously in Figure 2-1. The repetition process for the engine was described by the simplified method through the repetition of fuel droplets that continuously impinged on the hot wall surface. However, the piled-up deposit process in an engine was described by the method through the non-volatile fuel components that remain and further turn into a carbonaceous deposit layer for every droplet impingement.

The repetition and piled-up deposit processes in an engine are described through the single droplet simulation by using the simplified method which is referred in this study as a hot surface deposition test (HSDT). Thus, the aim of HSDT is to simulate the deposition on the wall in an engine’s combustion chamber and also to investigate deposit development, mechanisms and factors that effect the deposit formation.

Figure 2-2 Repetition process of deposit formation on a hot wall surface
2.2 Methodology and hot surface deposition test

Figure 2-3 shows the general method of deposit investigation in this study. Deposit investigation in this study involves two different methods. First, by using a simplified method that uses the single droplet repetition apparatus which is referred to as hot surface deposition test (HSDT) and the second method is by using a real engine which is referred to as the engine deposition test (EDT). The deposition results between these two methods in terms of deposit development, deposit composition and deposit effects on surface temperatures were compared in order to find out their similarities in deposit formation. From the similarities that were obtained, the availability of HSDT was discussed. The availability of HSDT in this study means how capable HSDT is producing results or effects similar to EDT.

Figure 2-3 General method of deposit investigation

A single droplet repetition apparatus was used to conduct the deposition test referred to as HSDT. The main results for HSDT are deposit development,
deposit surface temperature, deposit composition and deposit features. In this study, HSDT was used to investigate various factors that effect the deposit formation on a hot surface such as the surface temperature effect, the blend ratio and wet/dry condition effects, and also the effect of various types of fuel on deposition.

Various surface temperatures that occur in the combustion chamber [84] will cause a different droplet interaction with the surface [85, 86]. Due to these reasons, it is important to obtain the evaporation characteristic for each type of fuel used in this study. The evaporation test (ET) was conducted to support HSDT in order to decide HSDT condition and also to explain the deposition process in this study. The evaporation characteristic obtained in this test will provide information such as droplet lifetime, maximum evaporation rate point (MEP) and droplet-surface interaction behavior during evaporation. Thus, from the information, an appropriate surface temperature corresponding to similar droplet-surface interactions in a real engine can be used in our deposition test. The HSDT used in this study can describe certain parts of deposit development in a real engine, especially for deposit formation caused by liquid fuel film adhered on wall surfaces in combustion chambers through fuel spray impingement.

2.3 Experimental apparatus and procedures

Two main experiments were conducted; a hot surface deposition test (HSDT) and an engine deposition test (EDT). However, as mentioned before, an evaporation test (ET) was also conducted as an additional test to determine HSDT conditions and to support the explanation of HSDT results obtained later on.

2.3.1 Hot surface deposition test (HSDT)

(1) Single droplet repetition apparatus

A single droplet repetition apparatus was used in ET and HSDT. A photograph of the single droplet repetition apparatus is shown in Figure 2-4. The apparatus consists of 1) hot surface plate; 2) heater; 3) droplet detector; 4) needle; 5) pinch cock; 6) fuel tube; 7) fuel tank; 8) thermocouple; 9) temperature controller; 10) detector system; 11) pulse generator; 12) pulse conditioner and 13) universal counter as shown by the schematic diagram in Figure 2-5.
A concave plate of aluminum alloy (JIS 2017S) was used as a hot surface plate. The plate was electrically heated and its surface temperature was controlled by a
temperature controller. The surface temperature was measured by a
thermocouple, where its tip is located at the center of the hot surface plate and
underneath the surface as shown in Figure 2-6. In the figure, the detailed
dimension of the hot plate is also provided. Temperature measured by the
thermocouple was not usually consistent with the real surface temperature of the
plate due to heat loss from its surface. Therefore, an infrared thermometer was
also used to obtain a more accurate surface temperature. The needle tip is located
80 mm ($L_h$) above the center of the hot surface to avoid pre-heating the test fuel
and to minimize error caused by the splash loss of droplets mass at impingement.
The impingement interval ($\tau_{imp}$) of droplets was controlled by adjusting the pinch
cock. The number of droplets impinged ($N_D$) was counted using an infrared laser
detector and counting equipment.

![Figure 2-6](image)

**Figure 2-6** Experiment apparatus of HSDT and hot plate dimensions

(2) **Evaporation test (ET) procedures**

The evaporation characteristics of tested fuels can be obtained through this
evaporation test. Fuels used in the evaporation test are Dodecane (DO: C\(_{12}\)H\(_{26}\)) and all fuels tested in HSDT. The mass of a single fuel droplet (\(m_D\)) and its diameter (\(D_d\)) were evaluated by the density of fuel (\(\rho_{\text{fuel}}\)) and mass of 100 droplets. Droplet mass for each type of fuel was slightly varied due to different values of density.

The temperature range of the evaporation test depended on the type of fuel tested and also the capability of the electric heater during the experiment. The maximum temperature range of the heater set during the evaporation test was approximately 125°C to 410°C. The maximum temperature fluctuation at a set point was 5°C due to the impingement and slow response of the heating equipment. After the required temperature was set, droplets were released from the needle tip to be impinged to the hot surface. For each temperature, at least three data are recorded to ensure the reliability of the data. To understand the behaviors of the droplets on the hot surface, the droplet-surface interaction behavior during evaporation was observed and illustrated.

**Figure 2-7** shows the illustration of droplet evaporation for pure (A) and multi-component fuel (B).

![Diagram of droplet evaporation](image)

**Figure 2-7** Droplet evaporation for pure and multi-component fuel
The droplet lifetime ($\tau_{\text{life}}$) for pure fuel such as DO was evaluated by a period from start when the droplet touched the hot surface and to end when evaporation of the droplet was completed. However, multi-component fuel droplet lifetimes were recorded until the remaining fuel was hard to vaporize and no more vapor was produced during the evaporation. For each tested fuel, evaporation characteristics that shows correlation between droplet lifetime and hot surface temperature were plotted as illustrated in Figure 2-8. Three important facts can be obtained in this figure including droplet lifetime at certain hot surface temperature, maximum evaporation rate point (MEP), and droplet-surface interaction behavior.

The data obtained from the evaporation characteristics of fuels are required as a reference in order to decide the surface temperature during the fuel deposition investigation and also to help in explaining the fuel deposition process later on.

![Diagram of evaporation characteristics](image)

**Figure 2-8** General features of evaporation characteristics

(3) HSDT procedures

For HSDT, the hot plate surface temperatures are referred to as indicated temperature ($T_i$ [°C]) and surface temperature ($T_s$ [°C]), where the first is measured by a thermocouple and the latter is by an infrared thermometer. A linear correlation for both temperatures was first calculated before each ET and HSDT was begun. Figure 2-9 shows the general correlation for both temperatures. The correlations can be used to give an approximation of actual
surface temperature.

Fuel droplets were repeatedly impinged on the hot surface of aluminum alloy at different impingement intervals. The amount of deposits for every 1,000 droplets was measured and a photograph of deposits was taken. Due to the sensitivity of microbalance, the hot surface needed to be cooled down before the measuring of the total amount of deposits at 1,000 droplets.

The hot surface temperature for deposition test was selected between saturated and Leidenfrost temperature, where wet conditions are located within this temperature range. As mentioned by Eckhause, et. al. [58], the wet condition is significant since the condition is an appropriate surface condition in the combustion chamber of a diesel engine.

\[
T_S = AT_i + B
\]

![Aluminum Alloy Surface Temperature](image)

Figure 2-9 Temperature correlation

Data for maximum and minimum surface temperatures of deposits \( (T_d) \) within the impingement interval were collected by using an infrared thermometer (MINOLTA IR-308) with emissivity of 0.90 to investigate the effect of heat transfer on deposition. **Figure 2-10** shows the measurement of deposit surface temperature by using the infrared thermometer. A minimum surface temperature of a deposit means the surface temperature of the deposit was measured at the impingement point just after the fuel droplet impinged on the deposit surface. However, a maximum surface temperature of a deposit means that the surface temperature of a deposit was measured at the impingement point just before the next droplet impinges on the deposit surface. The maximum surface temperatures of deposits and the evaporation characteristics of fuels were used to
estimate droplet lifetime for deposition tests. After the deposition test was completed, deposit composition that accumulated on the hot surface was analyzed by using a MEXA particulate analyzer (HORIBA, MEXA-1370PM).

![Diagram]

**Figure 2-10** Deposit surface temperature measurement

Test conditions for HSDT were summarized in **Table 2-1** where these conditions depend on the type of deposit investigations (Experiments No. 1 to No. 4) that will be explained in detail in four separate chapters.

**Table 2-1** HSDT conditions

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Investigation</th>
<th>Fuel</th>
<th>Impingement int.</th>
<th>Surface temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1 (Chapter 3)</td>
<td>Availability of the hot surface deposition test</td>
<td>DF, DF+1%L, DF+2%L</td>
<td>8</td>
<td>270</td>
</tr>
<tr>
<td>No. 2 (Chapter 4)</td>
<td>The effect of hot surface temperature on diesel fuel deposit formation</td>
<td>DF</td>
<td>5</td>
<td>270, 306, 327, 352, 367</td>
</tr>
<tr>
<td>No. 3 (Chapter 5)</td>
<td>Bio-blended diesel fuel deposits on a hot wall surface</td>
<td>DF, B100, B50, B20, B5</td>
<td>3, 5, 5, 8</td>
<td>306, 352, 352</td>
</tr>
<tr>
<td>No. 4 (Chapter 6)</td>
<td>Deposition characteristics of various types of diesel and bio-diesel fuels</td>
<td>DF, DFP, B100, B100C</td>
<td>5</td>
<td>352, 352, 308</td>
</tr>
</tbody>
</table>
2.3.2 Engine deposition test (EDT)

(1) Four-stroke DI diesel engine

A four-stroke single cylinder direct injection (DI) diesel engine was used in this test and the engine specifications are listed in Table 2-2. This test engine was an air cooled type single cylinder direct injection diesel engine.

The photograph and schematic diagram of the engine test bench are shown in Figures 2-11 and 2-12, respectively. To measure the combustion chamber deposition mass without dismantling the cylinder head, an aluminum plug was made and equipped to the cylinder head. Four thermocouples were inserted into the plug to measure the plug temperature and a heater was inserted to control the plug temperature. The plug position was determined in the combustion chamber in such a way that both surface plug and cylinder head were fitted. A thermocouple was inserted into the cylinder head to measure the cylinder head temperature near the plug.

<table>
<thead>
<tr>
<th>Engine Specifications</th>
<th>Engine Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine name</td>
<td>Robin engine</td>
</tr>
<tr>
<td>Engine model</td>
<td>DY41DS</td>
</tr>
<tr>
<td>Engine type</td>
<td>4-stroke OHV 2-valve</td>
</tr>
<tr>
<td>Cylinder:</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>1</td>
</tr>
<tr>
<td>Bore</td>
<td>82 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>78 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>412 cc</td>
</tr>
<tr>
<td>Top clearance</td>
<td>0.87 mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>21</td>
</tr>
<tr>
<td>Intake valve:</td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>16°BTDC</td>
</tr>
<tr>
<td>Close</td>
<td>126°BTDC</td>
</tr>
<tr>
<td>Exhaust valve:</td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>14°ATDC</td>
</tr>
<tr>
<td>Close</td>
<td>124°ATDC</td>
</tr>
<tr>
<td>Cooling type</td>
<td>Air cooling</td>
</tr>
</tbody>
</table>
Figure 2-11 Photograph of the engine deposition test bench

Figure 2-12 Schematic diagram of four-stroke single cylinder DI diesel engine
(2) EDT procedures

A specially made deposition test plug was set to detect the deposits in the combustion chamber where its location and dimensions are shown in Figures 2-13 and 2-14, respectively. A heater embedded in the plug was used and the heater temperature was set at \( T_h = 240 \degree C \) to maintain the plug temperature \( (T_p) \) at a temperature slightly higher than the cylinder head temperature \( (T_c) \). Thermocouples were used to measure the plug temperature and cylinder head temperature, and their locations are also shown in Figure 2-14. The excess air-fuel ratio \( (\lambda) \) was set at 2.4 for medium load engine operation and fuel was injected at 15 degrees before TDC. Engine speed was set at 1,200 rpm and ran up to 20 hours. At one hour intervals, the deposition plug was uprooted and the accumulated mass of deposits on the top surface was measured. The deposition mass was defined as the difference of plug mass before and after the experiment. The plug mass was measured by micro balance with 0.1 mg resolution. The plug was reset on the cylinder head without removal of accumulated deposits. After 20 hours, composition of the deposit that accumulated on the plug was analyzed by using a MEXA particulate analyzer.

Figure 2-13 Photograph of the deposition plug and its location in the cylinder head
2.4 Test fuel

The properties of the tested fuels in this study are listed in Table 2-3. Dodecane was used only for ET to obtain its evaporation characteristics in order to compare them with the evaporation characteristics of diesel fuel (DF: JIS No. 2) and was not used for HSDT. In the table there are two different types of diesel fuels: Japan standard diesel fuel (DF) and Philippine standard diesel fuel (DFP). The main difference between these two diesel fuels was that, DFP contained an additional 1% of coconut oil methyl ester (CME) based bio-diesel fuel.

Two types of bio-diesel fuels were used: B100 which is referred to as 100% palm oil methyl ester (PME) based bio-diesel fuel and the second is B100C which is referred to as 100% coconut oil methyl ester (CME) based bio-diesel fuel. The properties of the bio-blended diesel fuels such as B5, B20 and B50 are not stated here due to a lack of information. However, these fuels correspond to 5wt%, 20wt% and 50wt% of B100 blend with DF, respectively.
Table 2-3 Properties of tested fuels

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Dodecane</th>
<th>Diesel</th>
<th>Bio-diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td></td>
<td>C\textsubscript{12}H\textsubscript{26}</td>
<td>JIS No. 2</td>
<td>PNS</td>
</tr>
<tr>
<td>Density @15°C ((\rho\textsubscript{fuel}))</td>
<td>kg/m\textsuperscript{3}</td>
<td>749</td>
<td>850.0</td>
<td>860.0 max</td>
</tr>
<tr>
<td>Kinematic viscosity @ 40°C</td>
<td>mm\textsuperscript{2}/s</td>
<td>NA</td>
<td>4.0 max</td>
<td>2.0-4.5</td>
</tr>
<tr>
<td>Distillation T90</td>
<td>°C</td>
<td>-</td>
<td>320.0</td>
<td>370.0</td>
</tr>
<tr>
<td>Final boiling point</td>
<td>°C</td>
<td></td>
<td>214.5</td>
<td>350</td>
</tr>
<tr>
<td>Sulfur content</td>
<td>ppm</td>
<td>-</td>
<td>&lt;10</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbon residue (10% distillation)</td>
<td>% mass</td>
<td>-</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Cetane index</td>
<td></td>
<td>-</td>
<td>55.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Glycerides</td>
<td>% mass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monoglyceride</td>
<td>% mass</td>
<td>-</td>
<td>-</td>
<td>NA</td>
</tr>
<tr>
<td>Diglyceride</td>
<td>% mass</td>
<td>-</td>
<td>-</td>
<td>NA</td>
</tr>
<tr>
<td>Triglyceride</td>
<td>% mass</td>
<td>-</td>
<td>-</td>
<td>NA</td>
</tr>
</tbody>
</table>

*NA: Not available

Table 2-4 and Table 2-5 provide additional information for PME and CME in terms of properties and mass fractions of FAME, respectively. The data provided in the tables are adopted from Ejim, et. al. [13]. From these data, the differences between PME and CME are clearly stated.

Table 2-4 Additional properties of fuel for PME and CME [13]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>PME</th>
<th>CME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, (\rho\textsubscript{m})</td>
<td>g/mL</td>
<td>0.830 ± 2.3%</td>
<td>0.823 ± 2.3%</td>
</tr>
<tr>
<td>Surface tension, (\gamma\textsubscript{m})</td>
<td>mN/m</td>
<td>26.16 ± 6.0%</td>
<td>24.01 ± 5.2%</td>
</tr>
<tr>
<td>Kinematic viscosity, (\nu\textsubscript{m})</td>
<td>cSt</td>
<td>2.08 ± 3.1%</td>
<td>1.41 ± 2.3%</td>
</tr>
</tbody>
</table>

As shown in Table 2-4, density, viscosity and surface tension of PME are higher than for CME. These properties caused larger droplet size formation for PME during atomization in an engine. Ejim, et. al. [13] found in his study that the average SMD (Sauter mean diameter) for PME (25.1 microns) was greater than...
CME (20.1 microns). Hence, PME would produce poor atomization properties when compared to CME.

Table 2-5 Mass fractions of FAME for PME and CME [13]

<table>
<thead>
<tr>
<th></th>
<th>PME</th>
<th>CME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caprylic (C8:0)</td>
<td>0.001</td>
<td>0.083</td>
</tr>
<tr>
<td>Capric (C10:0)</td>
<td>0.001</td>
<td>0.060</td>
</tr>
<tr>
<td>Lauric (C12:0)</td>
<td>0.009</td>
<td>0.467</td>
</tr>
<tr>
<td>Myristic (C14:0)</td>
<td>0.013</td>
<td>0.183</td>
</tr>
<tr>
<td>Palmitic (C16:0)</td>
<td>0.439</td>
<td>0.092</td>
</tr>
<tr>
<td>Stearic (C18:0)</td>
<td>0.049</td>
<td>0.029</td>
</tr>
<tr>
<td>Oleic (C18:1)</td>
<td>0.390</td>
<td>0.069</td>
</tr>
<tr>
<td>Linoleic (C18:2)</td>
<td>0.095</td>
<td>0.017</td>
</tr>
<tr>
<td>Linolenic (C18:3)</td>
<td>0.003</td>
<td>-</td>
</tr>
</tbody>
</table>

Contrary to its benefits, bio-diesel fuel also has limitations such as low oxidation stability. The oxidation stability of bio-diesel fuels are mainly affected by temperature and oxygen. The oxidation of bio-diesel fuel will produce residual products that might worsen the formation of deposits on a combustion chamber’s wall. Park, et. al. [87] investigated oxidation stability for different types of bio-diesel fuel including PME. In the study, they concluded that the oxidation stability of bio-diesel fuels decreased as the content of the linoleic and linolenic acids increased. In Table 2-5, the total content of linoleic and linolenic acids for PME is greater than CME. This indicates that PME is less stable in oxidation when compared to CME. As deposit formation is the main consent in our study, the utilization of PME in an engine is expected to obtain greater tendency of deposit formation compare to CME.

The lubricant oil blended with DF in experiment No.1 is not listed in Table 2-3. However, the lubricant oil used in the experiment was SAE30 lubricant oil and its main properties, including kinematics viscosity and ash content are shown in Table 2-6. In the table, additional information was also provided for DF, DF+1%L and DF+2%L for comparison purpose. The kinematics viscosity for DF+1%L and DF+2%L were estimated by using the following equation.

\[
\nu_{Blend} = 79.62e^{-0.0346X}
\]
\[ \nu_{\text{Blend}} = \text{Kinematics viscosity of DF blends with SAE 30 lubricant [mm}^2/\text{s}] \]
\[ X = \text{Percentage of DF in blended fuel [%]} \]

Table 2-6 Properties of SAE 30 and DF blend with lubricant oil

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>DF</th>
<th>SAE 30</th>
<th>DF+1%L</th>
<th>DF+2%L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematics viscosity</td>
<td>mm$^2$/s</td>
<td>2.5 (30°C)</td>
<td>79.62 (40°C)</td>
<td>2.59</td>
<td>2.68</td>
</tr>
<tr>
<td>Ash</td>
<td>%</td>
<td>&lt;0.002</td>
<td>0.5</td>
<td>0.007</td>
<td>NA</td>
</tr>
</tbody>
</table>

DF blend with lubricant oil (SAE 30) was used for HSDT and EDT. There are various reasons for the utilization of DF blend with lubricant oil in our deposit investigation. The reasons are mentioned below:

1) EDT required engine operation up to 20 hours, requiring a large amount of fuel. In order to investigate the deposition of bio-diesel fuel, the amount of bio-diesel fuel needed is critical for EDT because it is difficult to get bio-diesel fuels in large quantities.

2) Bio-diesel fuels are not stable, even though in an atmospheric environment these types of fuel can easily oxidize. Furthermore, different types of bio-diesel fuels also have different degrees of oxidation stability.

3) Thus, we needed a standard fuel for the deposition test that was easier to handle. DF blend with lubricant oil is a suitable candidate for our deposition test. DF blended with lubricant oil acted as a surrogate fuel that had minerals and hydrocarbons of high boiling temperature. These were used to ensure fuel deposits in EDT and considered a better fuel for the deposition test.

4) From the literature, some previous research [7, 26-31] found that the major portion of deposits in a combustion chamber of an engine come from lubricant oil. Hence, the utilization of DF blend with lubricant oil provided some potential for investigating the lubricant effect on deposit formation for both HSDT and EDT.
Chapter 3

Availability of the hot surface deposition test (HSDT)

3.1 Introduction

In this chapter the results of HSDT and EDT experiments are compared to discover their similarities in terms of deposit formation. The availability of HSDT is discussed, where availability here means how capable HSDT is producing results or effects similar to EDT. The combustion process in EDT involved heating, evaporating and burning fuels. However, in HSDT study, the process was limited to heating and evaporating fuels due to the test being conducted under atmospheric conditions with no combustion. Thus, in this study, deposit formation on hot wall surfaces refers to the deposition that is caused by unburned fuel impingement. Parts of the physical mechanisms suggested by Lepperhoff, et. al. [26] such as the incorporation/impaction of particles and adsorption of gaseous components are neglected. However, other parts such as thin film formation and the reaction of hydrocarbons are included in our present study. HSDT is considered an initial research step in developing a simplified method to investigate engine deposits for various types of fuel.

Deposit investigation in this chapter used diesel fuel (DF: JIS No.2 Diesel fuel) and diesel fuels blended with 1% and 2% SAE30 lubricant oil which are referred to as DF+1%L and DF+2%L, respectively, as tested fuels. These blended fuels were surrogate fuels that had minerals and hydrocarbons with high boiling temperatures. These were used to ensure fuel deposits. Test conditions for EDT were mentioned in Chapter 2. However, for HSDT, the temperature of the aluminum alloy surface was controlled to maintain it at 270°C. As mentioned before, the wet condition is significant since it is an appropriate surface condition in the combustion chamber of diesel engines [58]. Thus, to obtain a wet surface condition, an impingement interval of 8 seconds was set with a maximum repetition number of 19,000. Then, the deposit composition of each tested fuel was analyzed by using a MEXA particulate analyzer.
3.2 Results

3.2.1 Hot surface deposition test results

(1) Evaporation characteristics of DF and DF blended with SAE 30

An evaporation test was conducted on DF, DF+1%L and DF+2%L. The purpose of this test is to discover the evaporation characteristic differences among those tested fuels. **Figure 3-1** shows the evaporation characteristics for DF, DF+1%L and DF+2%L.

**Figure 3-1** Evaporation characteristics for DF, DF+1%L and DF+2%L

All tested fuels seem to have similar droplet lifetimes for a surface temperature range approximately below $T_s=280^\circ$C. However, after the surface temperature increased above $T_s=280^\circ$C, the droplet lifetime for DF+1%L and DF+2%L was longer than the droplet lifetime of DF. This phenomenon was more obvious when the surface temperature reached the MEP temperature for each tested fuel. As expected, DF+2%L obtained the longest droplet lifetime at MEP, followed by DF+1%L and DF with evaporation lifetime of 7, 4 and 1 sec, respectively. This is probably due to the presence of lubricant oil that increased the density and viscosity of DF+2%L and DF+1%L compared to DF. DF+2%L and DF+1%L obtained a similar MEP temperature with DF as indicated in the figure. From these results, the initial deposit formation tendency can be predicted for the
deposition test. DF+2%L is expected to obtain a greater amount of deposits during the hot surface deposition test, followed by DF+1%L and DF.

In a real engine, due to small fuel droplet size, high temperatures and a high pressure environment, the evaporation characteristic of fuel droplets might shift to higher surface temperatures with shorter droplet lifetimes. This statement refers to information that obtained in the literature, regarding the evaporation of fuel at different conditions. Figure 3-2 to Figure 3-5 show the evaporation characteristics for different droplet diameter, pressure, gas temperature and surface roughness, respectively [66, 72, 88].

**Figure 3-2** Effect of droplet size on droplet lifetime [88]

**Figure 3-3** Effect of pressure on droplet lifetime [66]

**Figure 3-4** Effect of gas temperature on droplet lifetime [72]

**Figure 3-5** Effect of surface roughness on droplet lifetime [72]
In the deposition test, the continuous formation of deposits might change the deposit surface roughness. Referring to the result obtained by Mizomoto, et. al. [72] in Figure 3-5, fuel droplet evaporation characteristics will be slightly shifted.

The evaporation characteristics obtained were used to decide the test conditions for HSDT in this deposit investigation. There are a few considerations to determine the test conditions.

1) First is the existence of a wet condition on the hot plate surface. The impingement interval at certain hot surface temperatures must be shorter than the droplet lifetime of the tested fuel in order to create the wet condition. The droplet lifetime should also be long enough to ensure the existence of the wet condition until the end of the deposition.

2) The second consideration is the limitation of the infrared thermometer where its minimum temperature that can be measured is 250°C. For HSDT, the deposit surface temperature measured by the infrared thermometer is significant to obtain a deposit surface temperature fluctuation that can be used to explain the heat transfer effect during deposit formation.

3) The third consideration is to maintain the hot surface temperature for HSDT as close as possible to the heater temperature ($T_h=240^\circ C$) set in the engine deposition test.

From these considerations, the HSDT condition in this deposit investigation was set at a hot surface temperature of 270°C with an impingement interval of 8 seconds as mentioned at the beginning of this chapter.

(2) DF and DF blended with SAE 30 depositions on a hot wall surface

(2-1) Deposit development correlation

Before further discussion of the deposit development of DF, DF+1\%L and DF+2\%L, it is important to mention first the correlation used to describe deposit development in this study. There are many correlations that can be used to describe deposit development. Before the final expression for deposit development is concluded in this chapter, there are four empirical formulas considered to correlate the data obtained for deposit development. These formulas are describe by Equations (1), (2), (3) and (4), which are based on raw
data, total mass of fuel droplets (\(M_D\)), accumulated mass of fuel droplets (\(M_d\)) and mass of a single fuel droplet (\(m_D\)), respectively.

\[
\begin{align*}
M_R &= aN_D \\
\frac{M_R}{M_D} &= \alpha N_D^\beta \\
\frac{M_R}{M_d} &= \alpha N_D^\beta \\
\frac{M_R}{m_D} &= \alpha N_D^\beta
\end{align*}
\]

\(M_R\) = total deposits on a hot surface [g]
\(M_D\) = total mass of fuel droplets [g]
\(M_d\) = accumulated mass of fuel droplets [g]
\(m_D\) = mass of a single fuel droplet [g] = \((1/6\pi)\cdot(D_d)^3\cdot\rho_{fuel}\)
\(N_D\) = number of impinged droplets
\(D_d\) = diameter of a droplet [m]
\(\alpha\) = constant for initial deposition [-]
\(\beta\) = exponential index for deposition development [-]
\(a\) = constant for deposit development [-]

The correlations of deposit development described by Equations (1), (2), (3) and (4) are used to correlate the data obtained in this study, as shown in Figure 3-6, Figure 3-7, Figure 3-8 and Figure 3-9, respectively. The correlations in the figures were obtained through a simple linear regression method calculated by using the least squares method, except for the correlations stated in Figure 3-6. To obtain a zero amount of deposit for a zero repetition number, correlations in Figure 3-6 were obtained through a simple linear equation related to the origin point with an average data point for each tested fuel.

For comparison of these correlations, the coefficient of correlation (r) values are provided in Table 3-1 for Equations (2), (3) and (4). The values show the linearity of the data with the equations. The values of r closer to the value of +1 or -1 show that the equations have better correlation with the data plotted.
Table 3-1 Coefficients of correlation

<table>
<thead>
<tr>
<th>Tested fuel</th>
<th>Equation (2)</th>
<th>Equation (3)</th>
<th>Equation (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>0.99</td>
<td>-0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>DF+1%L</td>
<td>0.99</td>
<td>-0.95</td>
<td>0.99</td>
</tr>
<tr>
<td>DF+2%L</td>
<td>0.99</td>
<td>-0.27</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Figure 3-6 Deposit development correlation based on raw data

In terms of coefficients of correlation, **Equations (2) and (4)** show better correlation with the data obtained for DF, DF+1%L and DF+2%L compared to **Equation (3)**. Analyzing the raw data of deposit accumulated on the hot surface was also useful to describe the development of deposits as shown by **Equation (1)** in **Figure 3-6**. However, certain parts of the deposit development cannot be observed clearly such as at the initial stage of deposit development for DF and DF+1%L. Furthermore, for different conditions that obtained slow deposit developments which resulted in a small total amount of deposit, it might be difficult to differentiate between those results if the correlation is only based on the raw data.
Although Equation (2) has a good coefficient of correlation value, the equation did not show the actual deposit development. Compared to the raw data indicated in Figure 3-6, at a repetition number of 12,000, DF should obtain a lesser amount of deposit compared to DF+1%L. This actual difference for DF and DF+1%L data is not described well by the data plotted in Figure 3-7. Furthermore, the accumulated mass of fuel droplets used in the equation is not
constant and changes with the number of repetitions. Thus, the correlation describe by Equation (2) is not suitable if the maximum number of repetitions keeps changing during the deposit investigation. At a different maximum number of repetitions, the correlation for Equation (2) will keep changing.

**Figure 3-9** Deposit development correlation based on \( m_D \)

As mentioned before, Equation (3) is poor in correlating the data for deposit development of DF+2\%L. The value of the coefficient of correlation for DF+2\%L indicated in Table 3-1 is far from the value of -1, which showed a poor correlation with the data plotted in Figure 3-8. Furthermore, a negative gradient obtained by the equation for all tested fuels, as shown in the figure, makes Equation (3) unsuitable to describe the increase of deposit during the deposition test. Thus, in our opinion, the correlation indicated by Equation (4) is the best for our study at this moment. Equation (4) is sensitive to deposit development and able to differentiate different slow development of deposits. Furthermore, if the maximum number of repetitions is changing, it does not effect the correlation. Therefore, through this study, Equation (4) was used to describe the deposit development for HSDT, where the value of \( m_D \) was constant throughout the test and only depended on properties of the tested fuels for different HSDT conditions.

(2-2) Deposit development of DF and DF blend with SAE30

A logarithmic relationship between fuel deposits and the repetition number of droplet impingements was obtained to clarify the development tendencies of

\[
\begin{align*}
M_R/m_D &= 6.6\times10^{-3}N^0.51 \\
M_R/m_D &= 1.5\times10^{-2}N^{0.71} \\
M_R/m_D &= 3.8\times10^{-3}N^{1.02}
\end{align*}
\]
deposits as described by Equation (4). Figure 3-10 shows the HSDT results for DF, DF+1%L and DF+2%L at a hot surface temperature of $T_S=270^\circ C$ with an impingement interval of 8 seconds.

In Figure 3-10, the deposition mass $M_R$ was normalized by the mass of a single fuel droplet $m_D$. It was clear that normalized deposit masses $M_R/m_D$ for all tested fuels increased linearly with the repetition number of impingements. The value of coefficient $\alpha$ in the equation shows the amount of deposits at the beginning of deposition. However, the value of index $\beta$ depends on the deposit development rate during repetition of fuel impingements.

DF+2%L had a greater tendency in producing deposits than the tendencies of DF+1%L and DF. At a later stage of deposition with a repetition number of 12,000, DF+2%L ($M_R=274.0\text{mg}$) obtained approximately 4 times more deposit compared to DF+1%L ($M_R=60.8\text{mg}$), and these results were accordingly shown by their $\beta$ values. DF+2%L obtained the highest deposit development rate with $\beta=1.02$ compared to the other tested fuels. The development rate was considered a rapid development of deposit due to its $\beta$ value greater than 0.70.

![Figure 3-10 DF and DF blended with SAE30 deposit developments with number of droplets](image)

**Figure 3-10** DF and DF blended with SAE30 deposit developments with number of droplets.

At an initial stage of repetition ($N_D<4,000$), the deposit mass for DF+1%L was similar to DF. As shown in the figure for a repetition number of 1,000, the difference between the amount of deposits accumulated for DF+1%L ($M_R=11.1\text{mg}$) and DF ($M_R=10.9\text{mg}$) was only 0.2 mg which was approximately
2% greater than the amount of deposit accumulated for DF. This might be caused less by the effect of deposits and more by the effect of oxidation, where deposit surface temperatures were maintained almost constant and near the hot surface temperature. However, the increasing tendency at a later stage \( N_D > 4,000 \) was more important for fuel deposition because fuel deposition during long-term repetition was an actual problem that had to be investigated. For a repetition number of 12,000, DF+1%L \((M_R=60.8\text{mg})\) obtained 40% more deposit compared to DF \((M_R=42.7\text{mg})\). As for the situation with a high repetition number \((N_D >> 10,000)\), it was clear that a more rapid increase of deposits for DF+1%L was expected than for DF. It was clearly suggested by the fact that index \( \beta \) for DF+1%L was larger than that of DF.

DF blends with lubricant oil in this study have higher tendencies for deposit formation compared to DF. DF+2%L obtained the greatest total amount of deposit accumulated on the hot surface with the fastest deposit development rate, followed by DF+1%L and DF with \( \beta \) values of 1.02, 0.71 and 0.51, respectively.

### 3.2.2 Engine deposition test results

#### (1) Heat release rate results

**Figure 3-11** shows the results of the heat release rate for DF, DF+1%L and DF+2%L at \( t_R = 1 \) hour and 20 hours. According to Heywood [48], the heat release rate refers to the rate at which the chemical energy of the fuel is released by the combustion process. The results in the figures show that stable combustion was obtained during the engine operation, where there was no change in the heat release rate for all tested fuel at a running time of 1 hour and 20 hours. This condition is important for the engine deposition test in this study which requires a stable test condition for long period of time. These results guarantee the stable test condition for 20 hours of engine operation, producing more reliable results.

During the engine operation, a peak premixed heat release rate for DF+2%L and DF+1%L was lower than those in DF for both an engine running time of 1 hour and 20 hours as shown in **Figure 3-11(A)** and (B), respectively. We considered that the atomization of diesel spray deteriorated because the tested fuel viscosity was higher with lubricant oil. The addition of lubricant oil in diesel fuel had some effect on combustion which resulted in the peak depression of the heat release rate. As shown by the evaporation characteristics in **Figure 3-1**, the increase of droplet size and droplet lifetime for DF+2%L and DF+1%L compared
to DF can be used to explain the reasons for the peak depression that occurred in
this engine operation.

Figure 3-11 Heat release rate result for DF and DF blended with SAE30

(2) DF and DF blended with SAE 30 depositions in an engine

Figure 3-12 shows accumulated deposits on the plug and its relationship is
represented by Equation (5).

Figure 3-12 DF and DF blended with SAE30 deposit developments with number
of injections

72
\[
\frac{M'_R}{m_{inj}} = \alpha N_{inj}^\beta \quad (5)
\]

- \( M'_R \): total deposits on the plug [g]
- \( m_{inj} \): mass of a single shot injection fuel [g/injection]
- \( N_{inj} \): number of injections = \((1/2) \cdot (n_{rev}/60)\)
- \( n_{rev} \): engine revolutions [rpm]

From the figure, it is clear that DF blended with lubricant oil obtained a greater amount of deposit accumulated on the plug surface compared to DF. At the end of the deposition, DF blend with lubricant oil obtained more deposit compared to DF with DF+2%L \((M'_k=3.50\text{mg})\) and DF+1%L \((M'_k=2.45\text{mg})\) accumulated 1.4 and 0.7 times more deposits, respectively compared to DF \((M'_k=1.45\text{mg})\). For DF+2%L and DF+1%L, their amounts of accumulated deposits were competitive and fluctuated with each other as the number of injections increased. This is due to the alternation between formation and removal of deposits during the combustion process in EDT. The amount of deposit accumulated at 20 hours of engine operation for DF+2%L was greater than DF+1%L with approximately 43% more deposit obtained by DF+2%L.

According to the correlations in the figure, the normalized mass of deposits increased with the increasing the number of injections, and its tendencies were similar to the results obtained from HSDT. The development rate for DF+2%L was the highest, followed by DF+1%L and DF with \( \beta \) values of 0.47, 0.37 and 0.29, respectively.

The values of index \( \beta \) obtained from EDT were smaller than those from HSDT. As a result, the difference between DF+2%L and DF+1%L were not so obvious in EDT. The reason for this difference could be considered as follows. The deposit development in HSDT was only effected by the heating and evaporation processes. Whereas the combustion process additionally affected the development process of deposits in EDT. We considered that some part of the deposits in the combustion chamber was burned out by combustion. Then, the development rate of the deposits in EDT was generally less than that of HSDT.

### 3.2.3 Deposit composition of HSDT and EDT

**Figure 3-13** shows the total mass of deposit composition for HSDT and EDT.
The number of samples analyzed depended on the amount of deposits accumulated during both tests. Deposit samples for HSDT were divided into two or three lumps such as the upper and bottom parts of deposits to observe the composition differences at different parts of the deposits. However, there was no apparent difference between the compositions of the upper or bottom deposits. This meant that the deposits obtained by HSDT had homogeneous compositions. Since the total fuel and deposition surfaces of HSDT were far different with those of EDT, a detailed discussion of the similarity of both tests was difficult.

Figure 3-13 Absolute mass of deposit composition for HSDT and EDT

However, in terms of percentages, generally, soot and SOF in deposit samples for HSDT were greater than deposit samples for EDT. The soot fraction in the DF deposit was nearly similar for both HSDT and EDT, with the percentage slightly higher for HSDT. The HSDT obtained soot fractions in the DF deposit were approximately 39 to 47% whereas EDT obtained around 38 to 40%. On average, HSDT obtained a soot fraction for DF+1%L, 7% greater than that obtained for EDT. Although in DF+2%L for HSDT, the soot fraction was within 10 to 49%, due to more deposit samples compared to others, on average, the soot fraction was around 32% which was still greater than EDT, which was about 13%.
For SOF fraction in HSDT, all tested fuels obtained approximately 22 to 46%. However, for EDT it was around 5 to 11% only. These show that there were more SOF fractions in the deposit samples for HSDT as compared to EDT. Obviously for EDT, approximately 50 to 74% from all deposit samples contain other components such as ash which is far greater than HSDT that only obtained around 7 to 48%. In EDT, the presence of lubricant oil components in DF+2%L and DF+1%L clearly can be seen from this composition result due to the percentage obtained for other components in the deposit samples. DF+2%L and DF+1%L for EDT obtained a percentage of other components of over 70%, which was greater than DF which only obtained around 50%. In terms of sulfate components, there was no clear difference for all tested fuels in HSDT and EDT. The higher soot and SOF fractions and also lesser other components fraction for HSDT as compared to EDT were due to the fact that there was no combustion process in HSDT.

3.3 Discussion

3.3.1 Similarity between HSDT and EDT

In the combustion chamber during EDT, the burning spray hits against the side walls of the piston cavity, moves upward along the side walls and contacts the test plug surface. During this process, the plug surface is mainly exposed to the high temperature gases at 2000 to 2500 K including soot particles, soot precursors such as PAH, and evaporating lubricants. These components are deposited on the low temperature plug surface within some ten milliseconds in the expansion stroke of the engine cycle over many cycles. On the contrary, in the HSDT, large size droplets hit the hot surface at a low velocity and the resultant fuel film or droplets are slowly oxidized while the liquid fuel remains on the hot surface. The carbonaceous components and SOF thus generated by the slow oxidation remains as the deposit.

From the statements mentioned above, there is no doubt that HSDT has differences when compared with EDT. However, despite the differences, there are some similarities between these two tests in terms of deposition results and test conditions.
(1) Deposition results

(1-1) Deposit developments

In comparing the difference between deposit development for HSDT and EDT, Equation (4) and Equation (5) were used. Equation (4) was used due to the following considerations:

1) The constant mass of droplet for each impingement on a hot surface.
2) The continuous deposit formation on a hot surface.
3) The continuous repetition of droplets with a constant impingement interval

For EDT, Equation (5) had similar considerations with HSDT, such as:

1) The constant amount of fuel injected for each spray impingement.
2) The continuous deposit formation on a deposition plug.
3) The continuous repetition of spray injection with constant injection rate.

From these considerations, Equations (4) and (5) for HSDT and EDT, respectively have similar physical meanings. The repetition of a spray injection with a constant injection rate and constant amount of fuel injected for EDT can be described with a repetition of fuel droplets with constant impingement intervals and a constant mass of fuel droplets for HSDT. The difference was that HSDT was more focused and better described the deposition of individual fuel droplets. During the repetition process for both HSDT and EDT, continuous deposit formations on wall surface were obtained. Due to similar equations that have similar physical meanings, deposit development for both tests, in terms of the amount of deposit at the initial stage (coefficient $\alpha$) and the deposit development rate (index $\beta$), could be compared. Both tests obtained similar tendencies of deposit development for each type of fuel tested. However, due to combustion that involves high gas temperatures and also a relatively small area of deposition plug surface in EDT, a slower deposit development was obtained for EDT compare to HSDT.

For HSDT and EDT, both obtained higher rates of deposit development for DF blended with lubricant oil. $\beta$ values of DF+2%L and DF+1%L for HSDT were 1.02 and 0.71, respectively which is higher than DF which obtained 0.51.
However, for EDT, the values were much lower with 0.47, 0.37 and 0.29 for DF+2%L, DF+1%L and DF, respectively. In terms of $\alpha$ and $\beta$, both experiments showed similar tendencies when fuels were changed with the fuel that has higher tendency in deposit formation as shown in **Figure 3-14**. $\alpha$ values decreased, however $\beta$ values increased when tested fuel was changed for both HSDT and EDT. Obviously from the figure, the development rate differences between DF+2%L and DF for HSDT and EDT were 0.51 and 0.18, respectively. Hence, the fuel effect on $\beta$ appeared more plainly in HSDT than EDT because there was no combustion effect in HSDT.

![Figure 3-14 α and β values comparison](image)

**(1-2) Deposit composition**

Similarities between HSDT and EDT can also be checked by the comparison of deposit compositions for both experiments through a MEXA particulate analyzer able to detect soot, SOF and sulfate fractions in deposits.

In order to obtain the relative differences between compositions for both tests, fractions of soot, sulfate, SOF and others (ash) were derived by the base of total deposit mass. These results are shown in **Figure 3-15**. From the figure, the soot fraction was higher for DF in both HSDT and EDT. However, DF+1%L obtained soot fraction lower than DF for both tests. When the test fuel was changed to DF+2%L that has higher deposit formation tendencies, a soot fraction in DF+2%L deposit increased higher than DF+1%L, but still lower than DF for both tests. Thus, a similar tendency was obtained for soot fractions for both tests when fuel was changed to a fuel with higher tendencies in deposit formation.
Fewer soot fractions in the deposit for EDT compared to HSDT were due to part of the deposit in EDT which was burned and oxidized because of the high temperature environment during the combustion process.

Since there is no combustion process in HSDT, the fraction of SOF in HSDT was higher than EDT and the fraction of others (ash) in HSDT was less than EDT. However, the amount of SOF in the deposit depended strongly on the amount of deposits accumulated, deposit structure (porosity) and wet/dry conditions. For the sulfate fraction in both HSDT and EDT, there was no clear difference.

As a result, we concluded that both HSDT and EDT obtained similar tendencies in terms of soot fraction in deposits.

**Figure 3-15** Percentage of average deposit composition for HSDT and EDT

(1-3) Deposit surface temperature

**Figure 3-16** shows the results of deposit surface temperatures for HSDT. The minimum surface temperature of deposits appeared just after fuel dripping and the maximum appeared just before the next fuel dripping. It was clear that the maximum surface temperature at the early stage of repetition exceeded the original surface temperature of the hot wall. Due to more accumulated deposits at the later stage of deposition, the surface temperature of deposits decreased as the number of repetitions increased. We concluded that the surface oxidation of the deposit resulted in a high maximum temperature that exceeded the wall temperature.

In comparison to HSDT, **Figure 3-17** shows the fluctuation of plug and
cylinder head temperatures in EDT. Clearly it can be seen that during engine operation, plug temperature was higher than the temperature \(T_h=240^\circ C\) set for the heater embedded in the test plug. Deposit formation on the plug surface might have a significant effect on these results.

**Figure 3-16** Deposit surface temperature for HSDT

**Figure 3-17** Plug and cylinder head temperatures for EDT

The difference of surface temperature results for HSDT and EDT were due to different points of temperature measurement as shown in **Figure 3-18**. For HSDT, an infrared thermometer was used to measure surface temperature on the
surface of the deposit which was referred to as the surface temperature of deposit ($T_d$) in this study, where the temperature might be affected by the insulation effect (thermal conductivity effect) that prevents heat release from the heater and also exothermic effect due to surface oxidation from the deposit surface.

However for EDT, the thermocouple embedded in the plug measured a plug temperature ($T_p$) slightly lower than the plug surface. The temperature might be affected by the insulation effect (thermal conductivity effect) that prevents heat release from the combustion chamber during engine operation. The plug temperature can be considered a surface temperature of a deposit located very close to the wall surface of a deposition plug. From Figure 3-17, the plug temperature was higher than both the cylinder head temperature ($T_c$) and the heater temperature ($T_h$). This means that the insulation effect of the deposit involved in these results was caused by overheating of the cylinder head wall.

There are some similarities between HSDT and EDT in terms of surface temperature of deposit, where deposit surface temperature and plug temperature exceeded the set temperature. Furthermore, deposit surface temperatures for both tests were affected by the insulation effect of deposits that formed on wall surfaces in HSDT and EDT, which prevented heat release from the heat sources in both tests.

![Figure 3-18](image)

**Figure 3-18** Surface temperature measurement point for HSDT and EDT

### (2) Test conditions

Other than the similarities of the results obtained in this study, test conditions for HSDT and EDT also have some similarities. HSDT has test conditions similar to EDT in terms of hot wall surface temperature, wetting condition, heat transfer boiling regime and parts of deposit mechanism during the deposition test. The comparisons in this section were made by referring to the information
obtained from the literature.

(2-1) Wall surface temperature and wetting condition

For HSDT, the hot surface temperature range was set at 270°C. This temperature is within the surface temperature range for a wall surface of a combustion chamber in a diesel engine. As mentioned in the literature, surface temperature ranges in the combustion chamber for diesel engines are between 127°C to 327°C [58], 300°C to 350°C [89] and 200°C to 450°C [90] depending on the type and operating condition of the engine. Thus, the hot surface temperature set for HSDT in this chapter described the wall surface temperature for real diesel engines. However, for EDT in this study, the surface temperature was set at 240°C with 30°C difference compared to surface temperature that was set for HSDT.

Since HSDT was conducted in an atmospheric environment, the other condition that needed to be similar with a real engine is the wetting condition. As mentioned by Eckhouse, et. al. [58], for diesel engines, the appropriate hydrodynamic regime is the wetting regime. In this study, the existence of a wetting condition on the hot surface was obtained by setting the impingement interval less than the droplet lifetime at a surface temperature of 270°C.

(2-2) Heat transfer boiling regime

In terms of the heat transfer boiling regime, the temperature of 270°C in this study was within the nucleate heat transfer boiling regime. Nucleate and transition heat transfer boiling regimes are the dominant boiling regimes in a combustion chamber as mentioned by Senda, et. al. [84]. These heat transfer boiling regimes are illustrated in Figure 3-19. As shown by the evaporation characteristics for DF, DF+1%L and DF+2%L in Figure 3-1 for the nucleate and transition boiling regimes, the reason for the result of the heat release rate obtained for DF, DF+1%L and DF+2%L during EDT in Figure 3-11 can be understood. This showed some relationship between the results obtained in HSDT and EDT. By referring to Figure 3-2 to Figure 3-5 in the previous section, due to the high gas temperature and high pressure in the combustion chamber for EDT, the evaporation characteristics of tested fuel in atmospheric conditions might change and shift at a higher temperature zone during the deposition process in a real engine. Even though the evaporation characteristics of tested fuel changed during real engine operation, the wall surface temperature set at $T_h=240°C$, or the
plug temperature increased up to $T_c=250\degree C$ as shown in Figure 3-17, both wall surface temperatures are believed still within the nucleate boiling heat transfer regime during the deposition for EDT.

(2-3) Deposit mechanisms

In EDT, many factors are involved simultaneously in deposit formation such as thin liquid film formation, sticking/incorporation/impaction of particles, adsorption of gaseous components, reaction of hydrocarbons and compression of deposit layers [26]. It is impossible to obtain the same condition as EDT for a simplified method such as HSDT. However, in terms of deposit mechanisms, parts of deposit formation and removal mechanisms in real engines suggested by Lepperhoff, et. al. [26] are probably included in HSDT such as thin liquid film formation and reaction of hydrocarbons for deposit formation mechanisms. The thin liquid film formation is the most important mechanism because it will act as a contact medium for other depositable components such as soot particles. Without this contact medium, no depositable components in the combustion chamber are able to adhere to the wall. For removal mechanisms, oxidation of hydrocarbons, evaporation of volatile fractions, break off of porous deposits and wash off liquid remains are included in HSDT.
3.3.2 Availability of HSDT

Availability of HSDT here means how capable HSDT is delivering similar results or effects as EDT. From the similarities of HSDT and EDT in terms of deposition results and test conditions, HSDT was available to investigate the fuel deposit in an engine. HSDT was capable of delivering similar results as EDT in terms of deposit development and the amount of soot fraction in deposits.

The tendencies of different types of fuels in deposit formation occurred in the engine was described well with HSDT. The increased amount of deposit accumulated with the increased repetition number was similar with EDT. In EDT, the amount of deposit accumulated also increased with the increased number of injections. Further, the initial amount of deposit accumulated and the development rate of deposit for different types of fuel obtained in HSDT also show similar tendencies with EDT.

In addition, HSDT demonstrated a great potential for investigating deposit formation mechanisms because of the simplicity of the experiment and its ability to differentiate the development of deposits for various types of fuels. In EDT, the small increase of lubricant components that increase the amount of deposit accumulated such as for DF+2%L and DF+1%L did not show a big difference. However, the small increase of lubricant oil component in the test fuel resulted in a big difference for DF+2%L and DF+1%L in terms of the total amount of deposit accumulated and its deposit development rate for HSDT. This gives some advantages to HSDT, where the test is more sensitive to deposit development when compared to EDT. In terms of deposit composition, HSDT only obtained a similar result with EDT in terms of the soot fraction in deposits. However, for other components in deposits such as SOF and sulfate, there were no clear similarities. The similarities in terms of deposition results showed that HSDT has advantages over EDT in deposit investigation even though HSDT has a different environment from EDT. With limited similarities in test conditions such as hot surface temperature, wetting condition, heat transfer boiling regime and part of deposit mechanism, HSDT is still able to obtain similar results with EDT in terms of deposit development and soot fraction in deposits. This achievement was a good indication for the initial step for a simplified method to investigate the development of deposits.

Other than the above points, the results obtained from HSDT can be used to give a rough estimation of deposition in real engines through fuel evaluation and
surface temperature evaluation. The test can also reduce the cost of a real engine deposition test. For fuel evaluation, HSDT can describe the tendency of deposit development for newly developed fuels such as bio-fuels without testing the fuel in a real engine. This probably can reduce experiment costs and prevent engine damage due to the uncertainty of deposit development for new fuels. In terms of surface temperature evaluation, HSDT can be used to discover the optimum temperature that can produce a lesser amount of deposits on a hot surface for different types of fuels. Thus, preventive measures can be made in real engines by referring to the results obtained from HSDT.

3.4 Summary

In this chapter, the results are summarized as follows;
1. The equations for HSDT and EDT in this study can evaluate deposit development quantitatively such as for the initial amount of deposit accumulated and the deposit development rate of different types of fuels.
2. The results of deposit obtained in HSDT can be expressed using the following empirical equation:

\[
\frac{M_R}{m_D} = \alpha N_D^\beta
\]

Also, as for EDT, the deposition tendency can be shown using the following similar equation:

\[
\frac{M_{\text{inj}}'}{m_{\text{inj}}} = \alpha N_{\text{inj}}^{\beta}
\]

3. HSDT was capable of obtaining a similar result as EDT in terms of deposit development and soot fraction in deposits. Furthermore, the test conditions for HSDT are similar to some real engine conditions including wall surface temperature, wetting condition, heat transfer boiling regime and part of deposit mechanisms. Thus, the single droplet repetition apparatus could be used to estimate deposit development tendencies in real engines.
4. Deposit development characteristics obtained in this study showed that HSDT had a great potential to differentiate deposit development for various types of fuels. HSDT is sensitive to deposit development, where it can differentiate, although for two different test fuels having small tendencies in deposit formation.
Chapter 4

The effect of hot surface temperatures on diesel fuel deposit formation

4.1 Introduction

The main objective of this chapter is to investigate the effect of the hot surface temperatures on the deposit formation for diesel fuel (DF: JIS No. 2) by using the hot surface deposition test (HSDT). Through this study, the deposit formations for continuous droplet impingements at various hot surface temperatures were investigated (270°C, 306°C, 327°C, 352°C and 357°C). An impingement interval of 5 seconds was set with the maximum repetition number of 19,000. Additionally, from this investigation, the hot surface temperature region that had potential in reducing deposit formation was identified. This might help in understanding the more complex behaviors of deposit formation in real engines.

4.2 Results

4.2.1 Evaporation characteristics of dodecane and diesel fuel (JIS No. 2)

The evaporation characteristics for Dodecane (DO: C_{12}H_{26}) and diesel fuel (DF: JIS No. 2) are shown in Figures 4-1 and 4-2, respectively. Droplet lifetime, maximum evaporation rate point (MEP) and evaporation state are the three main characteristics in these figures.

Figure 4-1 shows the evaporation lifetime of DO where its droplet lifetime decreased gradually with an increase of surface temperature. The minimum lifetime of a DO droplet could be observed in a temperature region somewhat higher than its boiling point (B.P.=214.5°C). This temperature was called the maximum evaporation rate point (MEP) of its lifetime curve. The maximum evaporation rate point (MEP) referred to the point where the fuel droplet evaporated with the shortest lifetime. This point also indicated the limit for fuel droplet ability to stick on the hot surface during evaporation. Beyond this temperature, the fuel droplet started to detach from the hot wall surface due to the formation of fuel vapor between the droplet and the wall surface. Another characteristic point on the curve was the Leidenfrost temperature which is located around \( T_s = 287°C \). At
higher temperatures than the Leidenfrost point, single or plural spherical droplets were suspended on the hot surface. This state is indicated by open symbols: the non-single droplet status in the figure. In terms of fuel remains, DO left no remains after evaporation.

The evaporation characteristics of DF are shown in Figure 4-2. The evaporation lifetime before and up to the MEP region was similar to pure fuel (DO). However, due to multi-component hydrocarbons in the fuel, its detailed evaporation behavior was somewhat different from pure fuels. The MEP temperature was $T_S=357^\circ C$ and was slightly higher than the final boiling temperature of DF as shown in Table 2-3 (Chapter 2). The Leidenfrost point for DF could not be confirmed because the lifetime profile shifted far to the right side due to the high boiling points of various fuel components. Furthermore, the short lifetime region near MEP expanded. At the end of the evaporation, there were slight deposition remains on the surface due to various fuel components and carbon residue shown in Table 2-3.

The general features of single and non-single droplet states after impingement before and after the MEP temperature are illustrated in Figure 4-3. A single droplet state means a state of single droplet evaporation. In this state, the fuel droplet stuck on the hot surface when the surface temperature was lower than the MEP temperature as shown in illustration A1 (lens shape droplet) and A2 (vigorous boiling droplet). Due to the formation of fuel vapors after exceeding
the MEP temperature, the single droplet evaporation state in this regime means that the fuel droplet evaporated with a spherical shape droplet and detached from the hot surface as shown in illustration A3.

**Figure 4-2** Diesel fuel (JIS No. 2) evaporation characteristics

**Figure 4-3** General features of the single and non-single droplet states during DF evaporation
For the non-single droplet state, the evaporation features are referred as follows. Before MEP, the state means that a vigorous boiling of the fuel droplet produced a splash of small droplets (illustration B1) within the nucleate heat transfer boiling regime \[91\]. However, after MEP, the state means a break-up behavior (illustration B2) during the transition heat transfer boiling regime \[84, 92, 93\].

These characteristics controlled the initial wet/dry condition of the surface dominantly and also the droplet physical interaction with it. Next, the deposition test conditions shown in Table 4-1 were determined by using the information obtained from the evaporation test. Sub-cooled temperatures for the test condition also provided in the table.

<table>
<thead>
<tr>
<th>Table 4-1 MEP and HSDT conditions for tested fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEP:</td>
</tr>
<tr>
<td>MEP temperature, (T_{MEP}) °C</td>
</tr>
<tr>
<td>DO</td>
</tr>
<tr>
<td>231</td>
</tr>
<tr>
<td>HSDT conditions:</td>
</tr>
<tr>
<td>Impingement interval, (\tau_{imp}) sec</td>
</tr>
<tr>
<td>-</td>
</tr>
<tr>
<td>Hot surface temperature, (T_s) °C</td>
</tr>
<tr>
<td>-</td>
</tr>
<tr>
<td>Sub-cooled temperature</td>
</tr>
<tr>
<td>((T_s - T_{MEP}))</td>
</tr>
<tr>
<td>-</td>
</tr>
</tbody>
</table>

General meaning of sub-cooled temperature is a liquid temperature below boiling point. It was a general technical term uses in heat transfer problem when involves boiling and condensation on a hot surface. Due to multi-component fuels used in this study, the sub-cooled temperature is redefined by the following equation.

\[
\Delta T_{SUB} = T_s - T_{MEP}
\]

The sub-cooled temperature is referring to the temperature difference between the test surface temperature and the MEP temperature. Using this sub-cooled temperature, general meaning of temperature effect on evaporation and deposition in this study was clearly described.
4.2.2 Diesel fuel deposition on a hot surface

Deposit developments of DF at different surface temperatures are shown in Figure 4-4. The results show that the normalized deposit mass \( \frac{M_d}{m_D} \) increased logarithmic-linearly with the repetition number of impingements. In order to describe the deposit developments, the empirical relationship indicated by Equation (4) in Chapter 3 was used.

As shown by Figure 4-4, there was no guarantee that a higher surface temperature will obtain a lower total amount of deposit at the initial stage of deposition below a repetition number of 1,000. However, deposition within the transition boiling regime, such as for surface temperature of 367°C, obtained the lowest amount of deposit at the initial stage compared to deposition at other temperatures which occurred within the nucleate boiling regime. The data that could not be obtained for a surface temperature of 367°C at a number of repetitions below 3,000 proves the statement for less deposits occurring within the transition boiling regime.

![Figure 4-4 Development of DF deposits at various surface temperatures](image)

As the number of repetitions increases, higher surface temperatures tended to accumulate a lower amount of deposits compared to low surface temperatures. At the end of deposition, with a repetition number of 19,000, the lowest surface temperature \( T_S = 270°C \) accumulated an amount of deposit equal to \( M_d = 54.8 \text{mg} \) which was 45 times greater than the highest surface temperature set in this study.
which only accumulated an amount of deposit equal to $M_R = 1.2 \text{mg}$. In this study, surface temperatures close to MEP temperature have significant results in deposit reduction. At a repetition number of 9,000, the surface temperature of 327°C (30°C lower than MEP temperature) obtained a total amount of accumulated deposits of approximately $M_R = 3.3 \text{mg}$. When the surface temperature was set at 352°C (5°C lower than MEP temperature), the amount of deposit accumulated was $M_R = 1.5 \text{mg}$ with 55% reduction. However, more reduction was obtained for a surface temperature of 367°C (10°C higher than MEP temperature) with $M_R = 1.0 \text{mg}$, where 70% less deposit accumulated compared to 327°C.

For a longer number of repetitions, the development rate ($\beta$) of deposit formation has a great influence, where the higher surface temperature obtained a slow deposit development rate resulting in a smaller amount of accumulated deposits. The effect of the $\beta$ value clearly can be seen in the deposit development for surface temperatures of 306°C and 327°C. At a repetition number of 2,000, the amount of accumulated deposits for 306°C was $M_R = 1.0 \text{mg}$, which was 66% less compared to 327°C even though the surface temperature of 306°C was lower. However, at a later stage of deposition, due to the higher deposit development rate for 306°C ($\beta = 0.62$) compared to 327°C ($\beta = 0.42$), as the repetition number increased, the difference between the amount of deposit accumulated for 306°C and 327°C also decreased. At a repetition number of 17,000, the amount of deposit accumulated for 306°C was $M_R = 3.8 \text{mg}$, which was 14% less compared to that accumulated for 327°C. For a greater number of repetitions ($N_D >> 19,000$), a surface temperature of 306°C is expected to obtain a deposit amount exceeding the amount accumulated for a surface temperature of 327°C.

Obviously, in Figure 4-4, there were two types of deposit developments, that is single-stage and two-stage developments. As for surface temperatures at 270°C, 306°C and 327°C that were far lower than the MEP temperature, two-stage developments were observed consisting of initial (dotted line) and later (solid line) stages of deposition. However, under conditions of 352°C and 367°C that were very close to the MEP temperature, a single-stage development was obtained.

The values of $\alpha$ and $\beta$ for each deposit development in Figure 4-4 are provided in Table 4-2. The values of $\alpha$ and $\beta$ within the table’s grey region indicate that the deposition experienced not only non-overlapping but also a dry deposit condition that caused the slow development of deposits with low values of $\beta$ ($\beta < 0.60$). The non-overlapping condition only means that the droplet lifetime was less than the impingement interval. However, the dry deposit condition
means that the non-volatile fuel remains were completely transformed into dry deposits.

<table>
<thead>
<tr>
<th>Surface Temperature</th>
<th>$\alpha_{\text{Initial}}$</th>
<th>$\beta_{\text{Initial}}$</th>
<th>$\alpha_{\text{Later}}$</th>
<th>$\beta_{\text{Later}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_S = 270^\circ\text{C}$</td>
<td>6.0E-5</td>
<td>1.43</td>
<td>1.7E-1</td>
<td>0.42</td>
</tr>
<tr>
<td>$T_S = 306^\circ\text{C}$</td>
<td>2.0E-12</td>
<td>3.32</td>
<td>1.8E-3</td>
<td>0.62</td>
</tr>
<tr>
<td>$T_S = 327^\circ\text{C}$</td>
<td>4.1E-1</td>
<td>0.04</td>
<td>3.2E-3</td>
<td>0.57</td>
</tr>
<tr>
<td>$T_S = 352^\circ\text{C}$</td>
<td>2.1E-2</td>
<td>0.29</td>
<td>2.1E-2</td>
<td>0.29</td>
</tr>
<tr>
<td>$T_S = 367^\circ\text{C}$</td>
<td>-</td>
<td>-</td>
<td>7.5E-4</td>
<td>0.56</td>
</tr>
</tbody>
</table>

: Non-overlapping and dry deposit conditions

In explaining deposit development, slow deposit development refers to deposit development with $\beta < 0.7$, whereas rapid deposit development refers to $\beta \geq 0.7$. As for 270°C and 306°C, values of $\alpha$ at initial stages were very small. As such, it could be concluded that, beginning with repetition numbers less than probably 100, a lesser amount of deposits was accumulated compared to the conditions at 327°C and 352°C. However, at repetition numbers of 1,000, a surface temperature of 270°C gave the highest amount of deposits followed by surface temperatures of 327°C, 352°C, 367°C and 306°C.

Actually, the amount of deposits at the beginning really depended on droplet-surface interaction. A surface temperature that obtains a greater contact area between the impinged droplet and the hot surface will obtain a greater amount of deposit at the beginning of deposition. A lower surface temperature caused a slow formation rate of the deposit precursor. Both droplet-interaction and deposit precursor formation rate were the reason for a very small $\alpha$ of the initial stage. However, a lower temperature caused more fuel remains and the deposit development rate was high as shown by $\beta$ in its initial stage.

4.3 Discussion

4.3.1 Development process of DF deposits

(1) Classification of deposit development

In this chapter, DF deposit development can be classified into single-stage and
two-stage deposit development. Figure 4-5 shows the general deposit tendencies in this experiment. The single-stage deposit development has a similar development rate at both the initial and later stages of deposition. However for two-stage development, usually the condition obtaining higher deposit development rate at the initial stage is expected to obtain a slower deposit development rate at the later stage of deposition. This resulted in two stages of development. As observed from the results shown in Figure 4-4, the hot surface temperature has a significant effect in determining type of development stage, whether single or two-stage.

![Diagram of general deposit tendencies](image)

Figure 4-5 Diagram of general deposit tendencies

(1-1) Single-stage development of deposit

The single-stage deposit development was obtained when the surface temperature was at 352°C. Due to the small sub-cooled temperature (surface temperature difference relative to MEP temperature) and due to the short original droplet lifetime (around one second), a non-overlapping condition (\( \tau_{life} < \tau_{imp} \)) was attained at the initial stage. It resulted in a dry deposit condition where probably all the non-volatile fuel remains at the impingement point were completely transformed into dry deposits.

Reducing the sub-cooled temperature, the evaporation state tended to approach the state with break-up behavior shown in illustration B2 of Figure 4-3. This is probably the reason for the larger size of scattered deposits near the impingement point (Figures 4-6(A and B)). When the temperature was changed to 367°C, this feature was more dominant, as shown in Figures 4-6(C and D).
During the deposit development under both surface temperatures (352°C and 367°C), the impingement surface conditions probably changed due to the formation of deposits. It seems that the changes of temperature and roughness of actual deposit surface might alter the evaporation characteristic profile [43, 77] but the dry deposit condition was not changed.

![Diagram](image)

**Figure 4-6** Photo-picture of diesel fuel deposits at \(N_D=1,000\) and \(N_D=9,000\) for single-stage deposit development

**(1-2) Two-stage development of deposits**

The surface temperatures of 270°C, 306°C and 327°C were far lower than the MEP temperature. The initial droplet-surface interactions for these temperature conditions were within the nucleate heat transfer boiling regime due to their large sub-cooled temperatures. Two-stage development resulted under these surface temperature conditions.

As can be seen in **Figure 4-4** and **Table 4-2**, although the amount of deposits obtained for 270°C was the highest, its deposit development rate at a later stage was lower than for 306°C. This slow rate was caused by a slow formation rate of the deposit precursor even though a low temperature produced a large amount of non-volatile fuel remaining during the initial stage. When fuel droplets were continuously impinged on the deposit, the deposit precursor spread from the impingement point as shown in **Figures 4-7(A and B)** and the layer formation of deposit was retarded. Furthermore, by referring to **Figure 4-7(B)**, a huge mass of fuel remaining was splashing out of the impingement point. The reason for the
relatively low value of $\beta$ in the later stage of 270°C can also be explained by the increased oxidation of these splash deposits.

<table>
<thead>
<tr>
<th>$N_D = 1,000$</th>
<th>$N_D = 9,000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) $T_s = 270°C$</td>
<td>(B) $T_s = 270°C$</td>
</tr>
<tr>
<td>(C) $T_s = 306°C$</td>
<td>(D) $T_s = 306°C$</td>
</tr>
<tr>
<td>(E) $T_s = 327°C$</td>
<td>(F) $T_s = 327°C$</td>
</tr>
</tbody>
</table>

**Figure 4-7** Photo-picture of diesel fuel deposits at $N_D=1,000$ and $N_D=9,000$ for two-stage deposit development

As for surface temperatures of 306°C and 327°C, both conditions showed similar features in the initial stages (Figures 4-7(C and E)). At a later stage of 306°C, more non-volatile fuel (Figure 4-7(D)) without splashing was observed compared to 327°C (Figure 4-7(F)). A higher $\beta$ value resulted at a later stage for a test condition of 306°C.

A surface temperature of 327°C was also lower than the MEP temperature. The initial stage of deposit development (Figure 4-7(E)) was very slow with a low value of $\beta$. This slow rate of deposit development remained until a repetition number of 9,000. After that, the deposit development with a greater value of $\beta$ took place.

The original droplet lifetime for 327°C is approximately 7 seconds. At the initial stage, due to the higher deposit surface temperature, the droplet lifetime was reduced and these was a slightly shorter than the impingement interval. However, during the deposition process, the droplet lifetime became longer and
non-overlapping and a dry deposit condition during the initial stage might be changed. After a repetition number of 9,000, an overlapping and wet condition took place. The splash of non-volatile fuel remains in Figure 4-7(F) was evidence of the overlapping and wet deposit condition.

(2) $\alpha$ and $\beta$ values comparison

In order to explain the relationship between the values of $\alpha$ and $\beta$ in Table 4-2, Figure 4-8 is provided. It shows the values of $\alpha$ and $\beta$ at various sub-cooled temperatures. Combination of the values of $\alpha$ and $\beta$ determined the total amount of deposits accumulated during the deposition repetition. As the surface temperature increased, the disparity between the initial (dotted lines) and later (solid lines) stages of deposit development decreased. The surface temperature of 327°C showed a transition of deposit development. Its deposit development at the initial stage behaved similarly to the deposit development for a surface temperature that was close to the MEP temperature with a low value of $\beta$. However, at the later stage, its development changed with a resulting greater value of $\beta$. The development of deposit for surface temperature of 327°C was similar to the deposit development of 306°C at the later stage of deposition, with a value of $\beta$ for 306°C which was slightly greater than for 327°C.

As for 352°C and 367°C, both temperature conditions gave a deposit development shown by a single value of $\alpha$ and $\beta$. These single values of $\alpha$ and $\beta$, indicated the single-stage deposit development for both surface temperatures. The slow developments of deposits obtained for the surface temperature closes to the MEP temperature (352°C and 367°C) and for the initial stage of deposit development at 327°C were due to those surface temperatures experiencing non-overlapping and dry deposit conditions as indicated by the symbol of an arrow in the figure.
4.3.2 Surface of DF deposit

The detail surface features of deposits at $T_s = 367^\circ C$ is shown in Figure 4-9. The thermal decomposition of the remaining fuel formed a deposit precursor. A carbonaceous-like deposit as shown in Figure 4-9(A) resulted from this process. It was characterized by a black color similar to soot. Also, a kind of ash caused by oxidation was observed with this soot-like deposit. However, the non-volatile fuel that had not decomposed remained, and polymerization that formed heavy molecular weight components took place. The reflection of light in Figure 4-9(B) shows the typical features of varnish-like deposits. The lustrous surface was evidence of polymerized high molecule liquid deposits. Also, trap bubbles were evidence of high temperature evaporation from these liquid deposits.
4.3.3 Surface temperature of DF deposits

The deposit surface temperature and estimated droplet lifetime during impingement repetition are shown in Figure 4-10. The surface temperature of deposits \( T_d \) was different from the hot surface temperature \( T_S \). Its minimum appeared just after impingement and increased up to the maximum just prior to the next impingement. The droplet lifetime for every impingement was estimated by the maximum surface temperature of deposits and the evaporation lifetime shown in Figure 4-2.

A cooling effect by liquid fuel was dominant at the beginning of deposition. It reduced the surface temperature of deposits. Chemical reactions such as polymerization and oxidation took place after the repetition number increased. Due to oxidation, heat was released and the surface temperature of the deposit increased. After more deposits accumulated, the surface temperature of the deposits was slightly decreasing due to the effect of low thermal conductivity of deposits. This was clearly observed at the later stage of 270°C.

The maximum deposit surface temperature decreased at the later stage of deposition for surface temperatures that far lower than the MEP temperature (270°C, 306°C and 327°C). However, for surface temperatures that close to the MEP temperature (352°C and 367°C), the maximum deposit surface temperature increased due to the exothermic process during the repetition.
As for the surface temperatures of 270°C and 306°C, their droplet lifetimes were far longer than the impingement interval. Due to this long droplet lifetime, some of the liquid fuel of the previous impingement droplet remained at the time of the next impingement. Then, an overlapping impingement condition was maintained throughout the repetition.

However, when the surface temperature was changed to 327°C, the droplet lifetime was close to the impingement interval. Due to the maximum deposit surface temperature exceeding the hot surface temperature, the droplet lifetime was sometimes reduced from the original and became shorter than the impingement interval. Because of the thickness of the deposit layer increased at the later stage (repetition number greater than 10,000), the droplet lifetime also increased and an overlapping condition resulted.

As for deposit developments at surface temperatures of 352°C and 367°C, the surface temperatures of deposits tended to be maintained close to the hot surface temperatures. Thus, the estimated lifetime of a droplet was always less than the
impingement interval and the non-overlapping condition was completely maintained.

4.3.4 Wet/dry conditions

As mentioned by Eckhouse, et. al.[58], a wet condition is significant because it is the appropriate surface condition of the diesel combustion chamber wall. During the wet surface condition, lighter molecular compounds may evaporate and the heavier molecular compounds may remain on the surface. The unburned fuel that adheres on the combustion chamber wall involves vaporization and heating processes. The vaporization process determines the amount of fuel remaining. However, the heating process of the fuel remaining involves various chemical reaction processes such as thermal decomposition, polymerization and oxidation. Among these factors, only vaporization has been widely discussed in the literature [75-79] as mentioned previously. The other factors mentioned here have not been discussed in detail.

Figure 4-11 shows a schematic diagram of deposit development. At the start of repetition, overlapping or non-overlapping are the critical conditions of deposit development. These critical conditions lead to the wet or dry deposit formation process in the initial stage of repetition. As for the later stages, surface condition of deposits became another rate-controlling factor of deposit development.

There are three categories of single droplet impingement research in the available literature for deposit development. They are; (1) single droplet impingement on a dry clean solid surface [94-98], (2) single droplet impingement on liquid film [99], and (3) single droplet impingement on a porous surface [100]. The deposit development observed here involved these three categories of droplet impingement. However, a wet/dry condition seemed to be the most important factor for the development of deposits.

Figure 4-12 describes the definition of non-overlapping and dry deposit conditions. However, for overlapping and wet deposit conditions, the condition definitions are shown in Figure 4-13.
Figure 4-11 Vaporization conditions during deposit development

Figure 4-12 Non-overlapping and dry deposit conditions

In Figure 4-12, the non-overlapping condition means that the next impingement of a fuel droplet occurs at a condition where all volatile components are completely vaporized (A) or all non-volatile components are completely...
transformed into deposits (B). The deposit in the latter condition is also referred to as a dry deposit condition. However, for overlapping as shown in Figure 4-13, the overlapping condition means that the next impingement occurs during the condition where volatile components are not completely vaporized. The wet deposit condition refers to the deposit conditions that still have liquid fuel remains on the deposit surface.

**Figure 4-13** Overlapping and wet deposit conditions

**Figure 4-14** shows two general states of wet/dry condition during the deposit formation. The non-overlapping state shown by **Figure 4-14**(A) was observed when the droplet lifetime was shorter than the impingement interval. Generally, during the non-overlapping state, the surface temperature of deposits was maintained almost constant due to the lesser amount of deposit accumulated. Thus, no changes occurred in the droplet evaporation rate and in the deposit formation rate even if the droplet impingements continued. The maximum amount of deposit after evaporation of each droplet depends on the surface temperature. A higher surface temperature will obtain a lesser amount of deposit due to the lesser non-volatile fuel that remains on the surface. During a drying period after the evaporation of every impingement, a portion of the carbonaceous deposits was reduced due to oxidation. A longer non-overlapping period causes more deposit reduction. At the later stage of deposition, due to a lesser amount of deposit accumulated for these conditions, the evaporation rate, the deposit formation rate and the deposit reduction rate through oxidation are probably similar as at the initial stage of deposition. The deposit formation increment was low for this non-overlapping and dry deposit condition that caused a slow deposit development rate.
The overlapping state shown in Figure 4-14(B) is generally observed in a continuous wet deposit condition. The amount of deposit accumulated increases with the repetition of impingement. It depends on the overlapping period between two continuous droplet impingements. For each new droplet impingement, the amount of volatile and non-volatile fuel components that remain on the hot surface are increasing due to the incomplete evaporation and deposit formation processes of the previous fuel droplet. Thus, more deposits accumulate. The surface temperature of deposits is reduced below the hot surface temperature due to the low thermal conductivity of deposits. Thus, the deposit formation rate is reduced while a large amount of deposits is accumulated. At the later stage of deposition, due to the large amount of deposit accumulated for these conditions, the evaporation rate and deposit formation rate are reduced as shown in the figure. For these overlapping and wet deposit conditions, a generally higher deposit
development rate would be obtained compared to non-overlapping and dry deposit conditions.

4.4 Summary

The effect of sub-cooled temperatures from the MEP temperature \((T_S - T_{MEP})\) and the wet/dry condition of hot surfaces on fuel droplet deposition was investigated. The main results are summarized as follows.

1. The sub-cooled temperature from the MEP temperature effected deposit formation. Different sub-cooled temperatures showed different droplet-surface interactions, evaporation lifetime and wet/dry conditions where various deposit development features resulted.

2. The non-overlapping and dry deposit condition results in a lesser total amount of deposit that is described as slow deposit development. For the overlapping and wet deposit condition, the accumulation of a greater total amount of deposit resulted.

3. There are two types of deposit developments for DF; (1) two-stage development for surface temperatures lower than the MEP temperature (large sub-cooled temperature) and (2) single-stage development for surface temperatures close to the MEP temperature (small sub-cooled temperature).

4. The hot surface temperatures located near MEP temperature (small sub-cooled temperature) have potential to reduce deposit formation on the hot surface. Lesser non-volatile fuel remains, the existence of non-overlapping and dry deposit conditions, higher deposit surface temperature and higher oxidation rate of carbonaceous deposits were factors contributing to deposit formation reduction within this temperature regime.

5. In this chapter, the smallest sub-cooled temperature obtained values of \(\alpha\) and \(\beta\) smaller than that obtained by the largest sub-cooled temperature at the later stage of deposition. In terms of the value of \(\beta\), the smallest sub-cooled temperature \((\beta=0.29)\) obtained value of \(\beta\) approximately 31% reduction compared to the value of \(\beta\) for the largest sub-cooled temperature \((\beta=0.42)\). Although both conditions obtained a slow development rate of deposition \((\beta<0.70)\), the lower value of \(\alpha\) and \(\beta\) for the smallest sub-cooled temperature will ensure the smallest amount of deposit accumulated at the end of deposition although for a greater maximum number of repetitions.
Chapter 5

Bio-blended diesel fuel deposits on a hot wall surface

5.1 Introduction

The aim of this chapter is to investigate the deposition of diesel fuel, bio-diesel fuel and its blended fuel droplets impinging on a hot surface of aluminum alloy. The deposition of diesel fuel was conducted as a reference to compare with the results obtained. Other than that, the effect of the impingement interval on deposition was also investigated. The types of deposition development and factors that affect the fuel deposition will be identified at the end of the study.

Types of fuel tested were diesel fuel (DF: JIS No. 2), palm oil methyl ester (PME) based bio-diesel fuel (B100), and various percentage of bio-diesel fuel blended with diesel fuel which is refer as bio-blended diesel fuel (B50, B20 and B5). Bio-blended diesel fuels were DF blended with 50%, 20% and 5% of B100 by weight, which are referred to as B50, B20 and B5, respectively. The hot surface temperature was set at 306°C and 352°C with impingement intervals of 3, 5 and 8 seconds.

5.2 Results

5.2.1 Evaporation characteristics of bio-diesel fuel and its blends

Evaporation characteristics on a hot surface for all tested fuels are shown in Figure 5-1. The droplet evaporation lifetime, maximum evaporation rate point (MEP) and evaporation state are the three main characteristics shown in the figure.

The maximum evaporation rate point (MEP) is referred to as the temperature where an impinged fuel droplet evaporated with the shortest lifetime. The symbol of a single droplet means a state of single droplet evaporation, whereas a symbol of a non-single droplet means as follows. Before MEP, this symbol refers to the vigorous boiling which produces a splashing of small droplets (refer to illustration B1 in Figure 4-3) or broken film of fuel (refer to illustration B2 in Figure 6-3) within the nucleate boiling regime [91]. However after MEP, the symbol means a break-up behavior (refer to illustration B2 in Figure 4-3) during the transition boiling regime [84, 92, 93].
These characteristics could explain the initial wetting condition and also droplet physical interaction with the hot surface. The deposition test conditions were decided by using the information obtained in the evaporation test. The maximum surface temperature of deposits and diagram of evaporation lifetimes were used to estimate an evaporation lifetime for HSDT later on.

The evaporation characteristics of DF are shown in Figure 5-1(A), where its evaporation lifetime was gradually decreased with an increase of the hot wall temperature. Unlike DF, B100, as shown in Figure 5-1(B), there was a steep curve that indicated its lifetime decreasing faster than DF.

![Figure 5-1](image)

Figure 5-1 Evaporation characteristics for DF, B100 and bio-blended diesel fuels

B50 and B5 in Figure 5-1(C and E) respectively show that their lifetime profiles were similar to DF before the MEP region. However, the profile for B50 located at a higher wall temperature zone had a longer droplet lifetime at near
MEP temperature compared to others. As for the longer lifetime region before MEP, B50 and B5 seem to be affected by the DF component more than the B100 component.

As shown in Figure 5-1(D), B20 had similar evaporation characteristics to B100 before MEP. The steep profile before MEP in the figure shows that the B100 component in B20 had more influence than the DF component. Both B20 and B100 had evaporation lifetime profiles that decreased faster than DF, B50 and B5 when the surface temperature was increased. Generally, the evaporation characteristics before MEP for bio-blended diesel fuels were located between DF and B100 characteristics.

Table 5-1 summarizes MEP temperatures for the tested fuels. MEP temperature for DF was at $T_S=357{\degree}C$ and it was slightly higher than the final boiling temperature shown in Table 2-3 (Chapter 2). Also for B100, its MEP was observed at $T_S=361{\degree}C$, higher than $T_{90}$ of B100. MEP for B50 occurred at $T_S=380{\degree}C$ which was at the highest temperature with a longer evaporation lifetime compared to others. For B50, we expect that its MEP should be between the value of MEP for B100 and B20 with an MEP value around $361{\degree}C$ or $362{\degree}C$. However, MEP value obtained for B50 was higher than the expected value. The properties of B50 might be slightly changed due to auto-oxidation in an atmospheric condition during storage, where the process cannot be controlled in this study. This is probably the reason for the result obtained for B50.

| Table 5-1 MEP and HSDT conditions for DF, B100 and bio-blended fuels |
|------------------------|----------------|----------------|----------------|----------------|----------------|
|                        | DF            | B100          | B50           | B20           | B5            |
| MEP:                   |               |                |                |                |                |
| Surface temp., $T_S$ °C| 357           | 361           | 380           | 362           | 357           |
| HSDT conditions:       |               |                |                |                |                |
| Impingement int., $\tau_{imp}$ sec | 3, 5         | 5, 8          | 5, 8          | 5, 8          | 5, 8          |
| Hot surface temp., $T_S$ °C | 306, 352     | 352           | 352           | 352           | 352           |

5.2.2 Fuel deposits on a hot surface

(1) B100 and bio-blended diesel fuel deposits

HSDT was used to evaluate the differences of deposit development among many kinds of blended fuels. HSDT conditions near MEP temperatures were set by referring to the evaporation characteristics listed in Table 5-1. B100, B50, B20 and B5 were tested at $T_S=352{\degree}C$ with impingement intervals $\tau_{imp}$ of 5 and 8.
Figure 5-2 shows a deposit development with $\tau_{imp}=5\text{sec}$. The accumulated deposit mass for B100 was largest among the tested fuels with the amount of deposit accumulated for 9,000 repetitions was $M_R=73.3\text{mg}$, which was 2 times higher than that obtained for the fuel with the lowest blend ratio (B5) that obtained $M_R=24.3\text{mg}$. At $T_S=352^\circ\text{C}$, the evaporation characteristics of B100 show its initial evaporation lifetime was $\tau_{life}=6\text{sec}$ which was longer than the impingement interval set up here. It means that a wet condition was maintained and caused the accumulation of heavy molecular weight substances on the surface at the initial stage of impingement repetition.

The result in Figure 5-2 also shows the accumulated deposits for B50 were less than other tested fuels although an initial wet condition existed. For repetition 9,000 repetitions, the amount of deposit accumulated for B50 was $M_R=18.9\text{mg}$. This value was approximately 74% less than B100 that accumulated the highest amount of deposit at the same repetition numbers. For a longer period of repetition, B50 will accumulate more deposits than B20 and B5. This was proven by the reduced amount of deposit differences between B50 and B20, and also between B50 and B5. For 9,000 repetitions, the differences came to about 64% and 22% less deposit for B50 ($M_R=18.9\text{mg}$) compared to B20 ($M_R=53.1\text{mg}$) and B5 ($M_R=24.3\text{mg}$), respectively. However, when the repetitions were increased to 14,000, the difference became smaller, and was reduced to 53% less deposit obtained for B50 ($M_R=29.2\text{mg}$) compared to B20 ($M_R=61.7\text{mg}$). But at this repetition number, B50 already exceeded the amount of deposit accumulated for B5 ($M_R=28.5\text{mg}$) with 2% more deposit obtained. However, due to the lower mass of the droplets for B5 compared to B50, the $M_y/m_D$ value for B5 was slightly greater than the value for B50. The amount of deposit accumulated for B50 will exceed the amount of deposit accumulated by B20 and B5 with more repetitions ($N_D>>20,000$) owing to a higher deposit development rate for B50 compared to B20 and B5 at a later stage of deposition.

As for the deposits of the initial stage, deposits for B20 developed similarly to B100, even though the amount of deposit accumulated for B20 was greater than B100. However, after 4,000 repetitions, the deposit development rate for B20 was less than B100. For 9,000 repetitions, the amount of deposit accumulated for B20 was $M_R=53.1\text{mg}$, which was approximately 28% less than that obtained by B100 ($M_R=73.3\text{mg}$). Referring to the evaporation lifetime of B20, a dry condition obviously existed where less heavy molecular weight substance was accumulated on the surface at the initial stage. However, this condition was not
maintained in the later stage of deposition. At the later stage of B20 deposition, an overlapping and wet conditions existed that caused fuel remains splashing from the impingement point. The slow rate of deposit development at this stage is probably due to the further reduction of B20 deposits through the oxidation of splash deposits. As for B5, a dry condition was continuously maintained, where the deposits were less than B20 as was expected. B5 obtained 54% fewer accumulated deposits, compared to B20 at 14,000 repetitions.

![Figure 5-2 Deposit developments at \( \tau_{imp}=5\text{sec} \)](image)

**Figure 5-3** shows deposit developments with \( \tau_{imp}=8\text{sec} \) where relatively small amounts of deposits were obtained for all the test fuels except for B20. There was no clear difference among the deposit developments for B100, B50 and B5. Less than 5mg of accumulated deposits were obtained at the end of repetition, where a dry surface condition was expected to dominate during the deposition. A relatively huge amount of accumulated deposits was obtained for B20. At 9,000 repetitions, the amount of deposit accumulated for B20 was \( M_R = 54.6\text{mg} \), approximately 20 times greater than the average amount of deposit accumulated by B100, B50 and B5 (\( M_R = 2.6\text{mg} \)). This was unexpected owing to its evaporation lifetime being less than the impingement interval. From the B20 result, we concluded the formation of deposits at the initial stage of deposition was probably responsible for this result.
Figure 5-3 Deposit developments at $\tau_{imp}=8$sec

(2) DF deposits

The results of DF deposition for HSDT at near MEP temperature are shown in Figure 5-4. The initial evaporation lifetime of DF was $\tau_{life}=1$sec near the MEP temperature region. For 9,000 repetitions, the amount of deposit accumulated for $\tau_{imp}=3$sec ($M_R=2.0$mg) at $T_S=352°C$ was 0.5mg greater than that obtained for $\tau_{imp}=5$sec ($M_R=1.5$mg) which means 33% more deposit was accumulated when the impingement interval was shortened to 3 seconds. However, there was no apparent difference among deposits developments for $\tau_{imp}=3$sec and 5sec at $T_S=352°C$. A similar deposit development rate was obtained for both test conditions. During the experiment, the temperature of the hot surface fluctuated between $T_S=347°C$ and 352°C, but this fluctuation did not have a significant impact on the deposit development because the evaporation lifetime was almost constant throughout the experiment.

Next, the surface temperature was reduced to $T_S=306°C$ where the initial evaporation lifetime was $\tau_{life}=15$sec, resulting in a wet condition for $\tau_{imp}=5$sec. Here, wet condition means that liquid fuel of the previous impingement droplet remained at the time of the next droplet impingement. For 9,000 repetitions with $\tau_{imp}=5$sec, the amount of deposit accumulated for $T_S=306°C$ was $M_R=2.5$mg, 1mg greater than that obtained for $T_S=352°C$ with approximately 66% more deposit accumulated for a surface temperature of $T_S=306°C$. This means that a double increment was obtained when the surface temperature was reduced to 306°C.
compared to a shortened impingement interval of 3 seconds. Deposit development of DF at $T_S = 306^\circ$C with $\tau_{imp}=5$sec was faster than deposit development at $T_S = 352^\circ$C with $\tau_{imp}=3$sec as shown by the values of $\beta$ in Figure 5-4. By lowering the surface temperature to $T_S = 306^\circ$C, a greater effect on deposition was obtained rather than shortening the impingement interval to $\tau_{imp}=3$sec.

![Figure 5-4 DF deposit development at different temperatures and impingement intervals](image)

**Figure 5-4** DF deposit development at different temperatures and impingement intervals

### 5.3 Discussion

#### 5.3.1 Logarithmic expressions for fuel depositions

Logarithmic expressions for the above results are also shown in Figures 5-2, 5-3 and 5-4 for different conditions and tested fuels. A greater value of coefficient $\alpha$ indicates that more deposit mass is produced at the initial stage of deposition test. The value of $\alpha$ is much affected by droplet-surface interaction and also deposit formation from fuel at certain surface conditions. Fuel that had easy deposit formation characteristics and large droplet contact areas with the hot surface might result in a higher value of $\alpha$. Index $\beta$ is dependent on the deposit development rate. For rapid development of deposits, $\beta \geq 0.70$ will be obtained, however $\beta < 0.70$ will correspond to slow development.

**Table 5-2** summarizes coefficient $\alpha$ and index $\beta$ obtained for all tested fuels.

<table>
<thead>
<tr>
<th>Diesel fuel (JIS No. 2)</th>
<th>Surface: Aluminum Alloy (JIS 2017S); $L_s = 80$ mm</th>
<th>$D_{d, ave} = 2.3$ mm; $m_{D, ave} = 5.4$ mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface temperature, $T_s = 352^\circ$C</td>
<td>Impingement interval = 5±1 seconds</td>
</tr>
<tr>
<td></td>
<td>Surface temperature, $T_s = 352^\circ$C</td>
<td>Impingement interval = 3±1 seconds</td>
</tr>
<tr>
<td></td>
<td>Surface temperature, $T_s = 306^\circ$C</td>
<td>Impingement interval = 5±1 seconds</td>
</tr>
<tr>
<td></td>
<td>---</td>
<td>Initial stage --- Later stage</td>
</tr>
<tr>
<td>( M_r/m_D = )</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$9.5 \times 10^{-3}N_D^{0.29}$</td>
<td>$2.1 \times 10^{-2}N_D^{0.19}$</td>
<td>$1.81 \times 10^{-3}N_D^{0.62}$</td>
</tr>
</tbody>
</table>

**Table 5-2** total relative deposition mass $M_r/m_D$ for different conditions and tested fuels.
These values did not fit with the deposition development at less than 1,000 repetitions because the data at this stage could not be obtained due to the sensitivity limit of microbalance.

Table 5-2 Logarithmic expression values

<table>
<thead>
<tr>
<th>Condition</th>
<th>$N_d$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B100: $\tau_{imp}=5$sec, $T_s=352^\circ$C</td>
<td>1,000-9,000</td>
<td>$7.1\times10^{-4}$</td>
<td>1.07</td>
</tr>
<tr>
<td>$\tau_{imp}=8$sec, $T_s=352^\circ$C</td>
<td>1,000-15,000</td>
<td>$2.0\times10^{-3}$</td>
<td>0.60</td>
</tr>
<tr>
<td>B50: $\tau_{imp}=5$sec, $T_s=352^\circ$C</td>
<td>1,000-15,000</td>
<td>$7.5\times10^{-3}$</td>
<td>0.68</td>
</tr>
<tr>
<td>$\tau_{imp}=8$sec, $T_s=352^\circ$C</td>
<td>1,000-11,000</td>
<td>$1.3\times10^{-2}$</td>
<td>0.36</td>
</tr>
<tr>
<td>B20: $\tau_{imp}=5$sec, $T_s=352^\circ$C</td>
<td>1,000-4,000</td>
<td>$7.2\times10^{-4}$</td>
<td>1.12</td>
</tr>
<tr>
<td>$\tau_{imp}=8$sec, $T_s=352^\circ$C</td>
<td>4,000-14,000</td>
<td>$3.8\times10^{-1}$</td>
<td>0.36</td>
</tr>
<tr>
<td>B5: $\tau_{imp}=5$sec, $T_s=352^\circ$C</td>
<td>1,000-10,000</td>
<td>$1.5\times10^{-2}$</td>
<td>0.70</td>
</tr>
<tr>
<td>$\tau_{imp}=8$sec, $T_s=352^\circ$C</td>
<td>1,000-9,000</td>
<td>$3.5\times10^{-3}$</td>
<td>0.54</td>
</tr>
<tr>
<td>DF: $\tau_{imp}=5$sec, $T_s=352^\circ$C</td>
<td>1,000-9,000</td>
<td>$2.1\times10^{-2}$</td>
<td>0.29</td>
</tr>
<tr>
<td>$\tau_{imp}=3$sec, $T_s=352^\circ$C</td>
<td>1,000-9,000</td>
<td>$5.2\times10^{-2}$</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau_{imp}=5$sec, $T_s=306^\circ$C</td>
<td>2,000-17,000</td>
<td>$1.8\times10^{-3}$</td>
<td>0.62</td>
</tr>
</tbody>
</table>

There is no guarantee that a higher blend ratio will produce more deposits at the initial stage of deposition. However, for a later stage of deposition, the blend ratio probably is one of the factors in determining the deposit development rate and the total amount of deposit accumulated. From the results obtained above, for a longer period of repetition, index $\beta$ is more important and has more influence on fuel deposition than coefficient $\alpha$. In real engine operation, deposits might be peeled off from the hot wall surface and new deposits will again develop. It is important to have a low value of coefficient $\alpha$ and also low value of index $\beta$ at the initial stage of deposition. However, for deposits that are hard to peel off during engine operation, index $\beta$ should be low enough to prevent a huge amount of deposits.

5.3.2 Fuel and deposit properties of diesel and bio-blended diesel fuels

The above results show an initial wet condition on the hot surface was not the main factor for rapid deposit development for all tested fuels. The deposit development was also related to fuel composition. Probably, the oxidation of fuel components in B100, B50, B20 and B5 contributed to deposit formation. As shown in Table 2-3 (Chapter 2), the bio-diesel fuel used here contained some
impurities such as glycerides which might become the precursor of deposits.

Mono- and di-glycerides as well as tri-glycerides are associated with bio-fuel deposits in engine combustion. As mentioned by Fox et al. [101] oxidized glycerides which exist slightly in bio-ester fuel produces various oxidation compounds, including non-volatile matter and high molecular weight compounds. These compounds are expected to be the precursor of a relatively large amount of deposits for B100, B50, B20 and B5 as shown in Figures 5-2 and 5-3. However, there is no guarantee of more deposit formation by increasing the percentage of bio-diesel fuel components in blended fuels. As for B50 with $\tau_{imp}=5$sec and B20 with $\tau_{imp}=8$sec, neither case showed a clear impact of bio-diesel fuel and the initial wet condition produced more or less deposits.

Deposit structures also contributed to deposit formation, where it influences thermal conductivity and heat transfer of the deposits. Deposits with a compact structure may have higher heat conductivity and be more difficult to peel off compared with porous structures. The change of these thermal properties of the deposit effect the surface temperature of the deposit, responsible for determining the amount of non-volatile fuel remains during deposition. Furthermore, Zerda et al. [37] have mentioned that deposit growth is controlled by deposit structure that was modified by subsequent deposition.

Deposit features are shown in Figure 5-5 for 3,000 and 8,000 repetitions for different fuels with $\tau_{imp}=5$sec. Generally, a lesser amount of bio-diesel fuel component in fuel shows a reduction in deposit accumulation as indicated by the size of mound-like deposits.

Obviously, splashing traces are observed for B100, B50, B20 and B5. It indicates that the overlapping of plural droplet evaporations occurred within the impingement interval due to the evaporation lifetime extension caused by the existence of a wet condition.
Figure 5-5 Photo-picture of B100 and bio-blended diesel fuel deposits at $N_D=3,000$ and $N_D=8,000$ with $\tau_{imp}=5\text{sec}$

When its impingement interval was elongated from $\tau_{imp}=5\text{sec}$ to $\tau_{imp}=8\text{sec}$, the deposit features were drastically changed as shown in Figure 5-6. There were two types of deposit features: layer-like and mound-like deposits with compact and porous structures, respectively. Layer-like deposits appeared except for B20. The difference among these layer-like features was their deposit layer radius. Less bio-diesel fuel content in fuel caused a smaller radius of the deposit layer. This might be explained by the amount of deposits accumulated at the initial stage of deposition corresponding to the value of $\alpha$. B5 deposits were not easily peeled off compared to B100 and B50 deposits. This meant that B5 deposits had a compact layer and high thermal conductivity.
**Figure 5-6** Photo-picture of B100 and bio-blended diesel fuel deposits at $N_D=3,000$ and $N_D=8,000$ with $\tau_{imp}=8\text{sec}$

Layer-like DF deposits as shown in Figure 5-7 had a harder structure. Further, fewer deposits for DF was mainly caused by smaller content of carbon residue and impurities and also the absence of glyceride components. DF deposit was also hard to be peeled off. In other words the features of B5 deposits previously explained were similar to the original features of DF deposits shown in Figure 5-7.
5.3.3 Deposit formation mechanisms

The deposit surface temperature ($T_d$) was different from the wall surface temperature ($T_S$). Its minimum appeared just after impingement and increased up to the maximum just before the next impingement. The fluctuation of the deposit surface temperature was caused by the competition among the cooling effect (A), surface oxidation (B), and heat transfer (C) during deposit formation. Their domination is indicated by regions A, B and C in Figure 5-8, respectively. The estimated evaporation lifetime during the repetition is also indicated in the figure. The experimental results in the figure were rapid development for B100 and slow development for DF.

Generally for rapid development of deposits, the deposit surface temperature tended to be lower than the hot surface temperature at the initial stage of deposition and its initial evaporation lifetime was not maintained where an overlapping condition existed as shown by the result obtained in Figure 5-8.

For B100, a cooling effect by liquid fuel was dominant at the beginning of deposition and reduced the surface temperature (B100-A). Then, surface oxidation took part after the repetition number was increased (B100-B), where
heat was released and brought an increase of the deposit surface temperature. After more deposits accumulated (B100-C), the deposit surface temperature decreased due to the effect of low thermal conductivity of deposits. The effect of low thermal conductivity was greater than the oxidation effect. An overlapping condition with an increasing evaporation lifetime was observed during this deposition domain.

**Figure 5-8** B100 and DF deposit surface temperature fluctuations and droplet lifetime estimations

However, for DF, only a slight decrease (DF-A) and increase (DF-B) in the deposit surface temperature resulted, where its maximum temperature was within the hot surface temperature fluctuation. A non-overlapping condition was maintained from the beginning to the end of the deposition experiment. Due to a lesser amount of deposits with layer-like features of DF deposits, a cooling effect at the beginning and surface oxidation during the later stage were dominant factors for the slow deposit development. There was a minimum effect of thermal conductivity of the deposits.

While a dry condition was maintained, no liquid fuel accumulated on the surface at the time when the maximum deposit surface temperature was measured. Hence, there was no effect of thermal oxidation of liquid fuels, but oxidation of carbonaceous deposits took place even in the dry condition.

**Figure 5-9** provides a comparison of deposit surface temperature fluctuation and the estimated evaporation lifetime. The deposit surface temperature and deposit structure had a great effect on the evaporation of impinged fuel droplets. As shown in **Figure 5-9**(A and E), both of the maximum and minimum
temperatures of deposits surfaces decreased to lower values than the hot wall temperature during the middle and later stages of deposition.

Deposit surface temperatures lower than the hot surface temperature was caused by less heat transfer due to the large amount of deposits and its effect exceeded the slow oxidation of deposits. For B20 (Figure 5-9(E and F)), although non-overlapping was maintained at the initial stage of deposition, there were rapid deposit developments in both cases. Probably, the deposit precursor formation rate in these conditions was greater than the evaporation rate. A lower temperature far below the hot surface temperature might produce more accumulated deposits. It resulted in the lengthening of the evaporation lifetime and overlapping evaporation of droplets appeared at the middle and later stage of deposition.

Generally, for the slow development of deposits with $\tau_{mp} = 8\text{sec}$, deposit surface temperatures became higher than the hot surface temperature with increased repetitions. This was caused by the slow oxidation of deposits that had a compact layer structure. An increase of surface temperature resulted in a shorter lifetime of evaporation and the non-overlapping situation appeared as shown in Figure 5-9(B, D and H), respectively. Thus, fewer deposits were formed.

For B50 in Figure 5-9(C and D), the evaporation lifetime was reduced close to its impingement interval and caused a fluctuation between an overlapping and non-overlapping condition. However, non-overlapping was probably more dominant and fewer deposits were formed.
Figure 5-9 Deposit surface temperature comparison for B100 and its blends for 
\( \tau_{\text{imp}} = 5\text{sec and 8sec} \)

5.4 Summary

In this chapter, the results are summarized as follows;
1. It is not certain that a higher blend ratio will produce more deposits at the initial stage of deposition. The amount of deposit accumulated at the initial stage
of deposition is much affected by the droplet-surface interaction and deposit formation from fuel under certain surface conditions. Fuel characterized by easy deposit formation and a large droplet contact area with the hot surface might result in a higher amount of deposit at the initial stage. For the later stage of deposition, the blend ratio is probably one of the factors in determining the deposit development rate and the total amount of deposit accumulated.

2. A wet condition was not the main reason for rapid development of deposits but enhanced deposit accumulation. The existence of a dry condition was preferable to reduce deposit formation on the hot surface. HSDT indicated that bio-blended diesel fuel had some risk of engine deposits under a wet surface condition but the deposition development rate depended on the blend ratio.

3. For a greater number of repetitions, a greater blend ratio of bio-blended diesel fuel produced more deposits with a higher deposit development rate. In a real engine, other than engine performance, a greater blend ratio bio-blended diesel fuel also will cause problems such as engine damage and particulate matter emission to the environment. However, these problems depend on the deposit properties with two considerations:
   a) First, the deposits that stick on the wall and are hard to peel off during engine operation will cause more damage to the engine, especially for the parts involving movement, such as the pistons.
   b) Second, if the deposits are easy to peel off during engine operation, another problem is the particulate matters that will be emitted from the engine during the exhaust stroke.

   Thus, the best bio-blended diesel fuel is with the lowest blend ratio. In this study, probably B5 is the best where less deposits accumulated for a greater repetitions process, whether in HSDT or in a real engine. Due to the fewer deposits accumulated, the problems mentioned above can be minimized.

4. The competition phenomena during deposition process is significant. The rapid development of deposits generally experienced overlapping and wet conditions, a cooling effect, an oxidation effect, and a low thermal conductivity effect. The low thermal conductivity effect was more dominant at the later stage of deposition, increasing the possibility of more deposits. However, for a slow development of deposit experiencing non-overlapping and a dry deposit condition, a cooling effect and an oxidation effect were more dominant, where at the later stage, the oxidation effect greatly influenced the maintenance of the deposit surface temperature, that further maintained a lesser accumulated deposits.
Chapter 6

Deposition characteristics of various types of diesel and bio-diesel fuels

6.1 Introduction

In this chapter, the main objective is to investigate deposition characteristics of different types of diesel fuels and bio-diesel fuels. Through this study, mechanisms and factors influencing deposit formation for diesel and bio-diesel fuels can be understood. Further, fuels having a greater potential in reducing deposit formation tendencies can also be identified. The diesel fuels tested were Japan standard (DF): JIS No.2 and Philippines national standard (DFP). However, the bio-diesel fuels tested here were esterized fuels made from palm oil (PME) and coconut oil (CME) which refer to B100 and B100C, respectively. The temperature of the aluminum alloy surface (JIS 2017S) was controlled to maintain it at 352°C or 308°C. An impingement of 5 second intervals was set for all tested fuels with a maximum 19,000 repetitions.

6.2 Results

6.2.1 Evaporation characteristics of various types of diesel and bio-diesel fuels

Figures 6-1 and 6-2 show the evaporation characteristics for diesel fuels and bio-diesel fuels, respectively. Droplet lifetime, maximum evaporation rate point (MEP) and evaporation state were the three main characteristics.

The maximum evaporation rate point (MEP) refers to the point where an impinged fuel droplet evaporated with the shortest lifetime. The point also indicates the limit point for fuel droplet ability to stick on the hot surface during evaporation. After the point, the fuel droplet starts to detach from the hot surface due to the formation of fuel vapor between the fuel droplet and the hot surface.
The general features of single and non-single droplet states after impingement for the before and after MEP region are illustrated in Figure 6-3. A single droplet state means a state of single droplet evaporation. At this state, the fuel droplet stuck on the hot surface when the surface temperature was lower than the
MEP temperature as shown in illustration A1 (lens shape droplet) and A2 (vigorous boiling droplet). Due to the formation of fuel vapor after exceeding the MEP temperature, single droplet evaporation in this state meant that the fuel droplet vaporizes with a spherical shape droplet and detaches from the hot surface as shown in illustration A3.

**Figure 6-3** General features for the single and non-single droplet states during diesel and bio-diesel fuel droplet evaporation

For the non-single droplet state, the evaporation features are referred to as follows. Before MEP, the state means a vigorous boiling of the fuel droplet producing a splashing of small droplets (illustration B1) or a broken film of liquid (illustration B2) within the nucleate boiling regime [91]. However, after MEP, the state means a break-up behavior (illustration B3) during the transition boiling regime [84, 92, 93].

These characteristics controlled the initial wetting condition dominantly and also the droplet physical interaction with the hot surface. Then, the deposition test conditions were decided by using the information obtained from the evaporation test as shown in **Table 6-1**.

The droplet lifetime profile before MEP for DF and DFP were very similar. However, DFP obtained a slightly lower value of MEP, and at that point, a longer droplet lifetime was obtained for DFP. The droplet lifetime for DFP at MEP
temperature was approximately 4 seconds compared to DF that obtained a droplet lifetime of 1 second at its MEP temperature. As for the different behavior of B100C in Figure 6-2, it had a shorter droplet lifetime before MEP compared to B100. Furthermore, MEP for B100C was far lower than MEPS of B100, DF and DFP. MEP values for all tested fuels are also shown in Table 6-1. As mentioned previously in Chapter 4, sub-cooled temperatures in Table 6-1 refer to the temperature difference between the test surface temperature and the MEP temperature.

| Table 6-1 MEP and HSDT conditions for diesel fuels and bio-diesel fuels |
|-----------------|-------|-------|-------|-------|
| MEP:            |      |       |       |       |
| Surface temp., $T_S$ °C | 357   | 355   | 361   | 317   |
| HSDT conditions:|      |       |       |       |
| Impingement int., $t_{imp}$ sec | 5     | 5     | 5     | 5     |
| Hot surface temp., $T_S$ °C | 352   | 352   | 352   | 352, 308 |
| Sub-cooled temperature $(T_S-T_{MEP})$ | -5    | -3    | -9    | 35*, -9 |

* means the test surface temperature was within transition boiling regime

From the evaporation test, the amount of deposits accumulated can be preliminarily predicted. DF and DFP will obtain a similar amount of deposits because their evaporation characteristics are similar. B100C probably has the potential to obtain far more reduction in the amount of deposits compared to B100. By referring to Figure 6-2, there are two reasons for the B100C deposit reduction: 1) Lower MEP value; and 2) shorter lifetime of droplets before MEP. At the same surface temperature as the temperature near MEP for B100, B100C droplets experienced a droplet-surface interaction within the heat transfer transition boiling regime where the droplets were not always attached on the hot surface although the droplets obtained a longer lifetime due to the lower value of MEP for B100C. For the lower temperature condition less than MEP of B100C, fewer amounts of deposits will be obtained for B100C because of its shorter lifetime compared to B100.

6.2.2 Deposition of various types of diesel fuels on a hot surface

DF and DFP depositions for HSDT at near MEP temperature are shown in
Figure 6-4. An apparent difference which was unexpected prior to the test was obtained for a test condition at $T_s=352^\circ\text{C}$ with $\tau_{imp}=5\text{sec}$.

In the figure, the deposition mass $M_R$ was normalized by the mass of a single fuel droplet $m_D$. It was clear that normalized deposit masses $M_R/m_D$ increased linearly with the repetition number of impingements.

![Graph showing deposition mass versus number of droplets for DF and DFP](image)

**Figure 6-4 Development of DF and DFP deposits**

We expected both DF and DFP to obtain a slow development of deposits due to their similar evaporation lifetime before MEP. Further, $\beta$ value for DFP was expected to be slightly higher than DF because at the test condition, DFP has an evaporation lifetime slightly longer than that for DF at a surface temperature of 352°C. However, the results showed an obvious difference probably because of DFP containing 1% B100C. At the very beginning of deposition, with a repetition number of 1,000, the difference between the amount of deposit accumulated by DFP ($M_R=1.7\text{mg}$) and DF ($M_R=1.5\text{mg}$) was approximately 0.9mg. After the repetition number increased to 9,000, DFP ($M_R=20.7\text{mg}$) obtained 13 times more deposit compared to DF ($M_R=1.5\text{mg}$), with the difference of 19.2mg. B100C content has a significant effect on DFP properties such as density and T90 as shown in Table 2-3 (Chapter 2). These properties caused a greater amount of fuel remains for DFP during impingement compared to DF. Furthermore, the DFP droplet lifetime was longer than DF under the same test conditions. By referring to
the fuel evaporation characteristics, the initial droplet lifetime for DF was \( \tau_{life}=1\text{sec.} \) However for DFP, its droplet lifetime was approximately \( \tau_{life}=4\text{sec.} \)

### 6.2.3 Deposition of various types of bio-diesel fuel on a hot surface

B100 and B100C were tested at \( T_s=352\,^\circ\text{C} \) with \( \tau_{imp}=5\text{sec} \) by using HSDT to investigate the deposition difference among bio-diesel fuels. Further, the additional test condition at \( T_s=308\,^\circ\text{C} \) with \( \tau_{imp}=5\text{sec} \) for B100C was tested to clarify the differences between B100C and B100 test results. **Figure 6-5** shows the deposit developments for these bio-diesel fuels.

This figure shows that B100 resulted in the highest total amount of deposits accumulated on a hot surface. The value of \( \beta \) describing the deposit development rate was high and was categorized as a rapid development. During B100 deposit formation, a wet condition continuously occurred and caused a greater amount of heavy molecular weight matter to accumulate on the hot surface.

**Figure 6-5 Development of B100 and B100C deposits**

B100C showed a slow development of deposits for a test condition of \( T_s=352\,^\circ\text{C} \) with \( \tau_{imp}=5\text{sec} \). Only a small amount of deposits was accumulated on the hot surface at the end of the repetitions. By comparing the amount of deposit accumulated for B100C at a repetition number of 9,000 with B100, B100C

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<table>
<thead>
<tr>
<th>Bio-diesel fuel</th>
<th>Surface: Aluminum Alloy (JIS 2017S)</th>
<th>( L_s = 80\text{mm} )</th>
<th>Impingement interval = 5±1 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>B100: ( D_d=2.4\text{mm}; m_D=5.9\text{mg}; T_s=352,^\circ\text{C} )</td>
<td>B100: ( D_d=2.3\text{mm}; m_D=5.2\text{mg}; T_s=352,^\circ\text{C} )</td>
<td>( \beta ) describing the deposit development rate was high and was categorized as a rapid development. The value of ( \beta ) describing the deposit development rate was high and was categorized as a rapid development. During B100 deposit formation, a wet condition continuously occurred and caused a greater amount of heavy molecular weight matter to accumulate on the hot surface.</td>
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obtained only \( M_R = 6.6 \text{mg} \) which is 10 times less deposit compared to B100 \( (M_R = 73.3 \text{mg}) \). During the deposition, it was observed that the surface condition probably changed due to the formation of a thin layer of deposits. It seems that the change of surface roughness due to deposit formation might alter the B100C evaporation characteristic profile to a profile having a shorter droplet lifetime \([38, 71]\). The surface temperature of the test condition became closer to the MEP point where the droplet lifetime was probably reduced below the impingement interval, resulting in the appearance of a dry condition.

Furthermore, at the initial stage of B100C deposition, B100C droplet evaporation was within the heat transfer transition boiling regime. In this regime most of the time, droplets were not attached to the hot surface due to the formation of fuel vapor under its droplets. Although the surface roughness after impingement changed, the heat transfer boiling regime remained the same. Droplets evaporated with vigorous boiling and movement on the hot surface. Sometimes it separated into a few minute droplets and sometimes the droplet was observed in a spherical shape, rolling on the hot surface.

Next, the surface temperature was reduced to \( T_S = 308^\circ\text{C} \) where the sub-cooled temperature for B100C \( (T_S-T_{\text{MEP}} = -9^\circ\text{C}) \) was similar to that for B100. The surface temperature was chosen to observe deposit development for B100C at a surface temperature below its nucleate boiling regime. The result obtained for B100C was also slow deposit development with \( \beta = 0.52 \) which was higher than the value of \( \beta \) obtained at \( T_S = 352^\circ\text{C} \) \( (\beta = 0.23) \). Less total amount of deposits for B100C were obtained for \( T_S = 308^\circ\text{C} \) compared to \( T_S = 352^\circ\text{C} \) as shown in Figure 6-5. At repetition number of 19,000, the amount of deposit accumulated for \( T_S = 308^\circ\text{C} \) was \( M_R = 5.4 \text{mg} \), which was 25% less deposit compared to that obtained for \( T_S = 352^\circ\text{C} \) \( (M_R = 7.2 \text{mg}) \). This result was due to shorter initial droplet lifetime for \( T_S = 308^\circ\text{C} \) \( (\tau_{ijc} = 5\text{sec}) \) compared to \( T_S = 352^\circ\text{C} \) \( (\tau_{ijc} = 8\text{sec}) \). However, a greater value of \( \beta \) for deposition at \( T_S = 308^\circ\text{C} \) will cause the amount of deposit accumulated for a larger number of repetitions to exceed the amount of deposit accumulated for \( T_S = 352^\circ\text{C} \).

In terms of droplet interaction at \( T_S = 308^\circ\text{C} \), the heat transfer boiling regime for the B100C droplet evaporation was within the nucleate boiling regime. Both test conditions \( (T_S = 308^\circ\text{C} \text{ and } T_S = 352^\circ\text{C}) \) for B100C had different physical interactions of fuel droplets with the hot surface. For \( T_S = 308^\circ\text{C} \), droplets stick to the hot surface and remain at the impingement point. Thus, a greater development rate of deposits was obtained. However, the lower value of \( \alpha \) obtained for \( T_S = 308^\circ\text{C} \) occurred due to the shorter droplet lifetime near MEP.
6.3 Discussion

6.3.1 Deposit features and logarithmic expressions for deposit development of various types of fuels

The development rate of deposits can be discussed with the index $\beta$ and its value for DF was $\beta=0.29$. The development rate of DF deposits was low and was categorized as a slow development with $\beta$ value less than 0.70. The condition was close to MEP and the impingement interval was longer than its droplet lifetime. Thus, a dry condition existed on the hot surface. Figure 6-6(A and B) shows that DF obtained a lesser amount of deposits accumulated with only a small increment of the amount of deposits as shown by the similar features of layer-like deposits in the figure.

Index $\beta$ for DFP was around 0.75. This means there was a rapid development of deposition ($\beta \geq 0.70$) compared to the results obtained for DF as shown by Figure 6-4. As shown in Figure 6-6(C and D), a relatively large amount of deposits was obtained for DFP.

![Figure 6-6](A-B) shows that B100 resulted in the highest total amount of deposits accumulated on a hot surface. Figure 6-7(C) shows a small amount of B100C deposits at the beginning of the deposition. This condition continued after the number of repetitions increased, as shown in Figure 6-7(D). These figures also described the deposit formation behavior for B100C when deposition occurred.
within the transition boiling regime. Physical interaction with the hot surface within this regime caused the deposits to remain in various locations on the hot surface. Furthermore, a dry condition caused carbonaceous deposits to change into white matter as can be seen in Figure 6-7(D) due to the long time they remained on the hot surface out of the impingement point area. A greater amount of B100C deposits was obtained at \( T_S = 308^\circ C \) as shown in Figure 6-7(E and F) compared to B100C at \( T_S = 352^\circ C \).

**Figure 6-7** Photo-picture of bio-diesel fuel deposits at \( N_D = 1,000 \) and \( N_D = 9,000 \)

**Figure 6-8** shows \( \alpha \) and \( \beta \) for different types of diesel fuels and bio-diesel fuels. For different types of diesel fuels, DFP showed a lower value of \( \alpha \) compared to DF. However, its \( \beta \) value was higher. These correlated well with previous results where fuels having a higher value of \( \beta \) might obtain a lower value of \( \alpha \). DFP with 1% B100C had a significant effect on the deposit development rate which contributed to a higher value of \( \beta \) compared to DF.

The value of \( \alpha \) showing the initial amount of deposits was much affected by droplet-surface interaction and deposit formation from fuel at certain surface conditions. Fuel having easy deposit formation characteristics and a larger
droplet contact area with the hot surface during impingement might result in a higher value of $\alpha$.

B100C showed a higher value of $\alpha$ but a lower value of $\beta$ compared to B100, although the test conditions were changed. As mentioned previously, different evaporation characteristics between B100C and B100 contributed to the results obtained in Figure 6-8. B100C had a greater potential in reducing deposit formation compared to B100. However, the B100C effect in DFP, having 1% B100C in composition, needs further investigation because the deposition behavior was unexpected since it showed a greater deposit development rate compared to DF. We suggest that B100C content had a significant effect on DFP properties such as density, T90 and evaporation characteristics.

![Figure 6-8](image)

**Figure 6-8** Comparison of $\alpha$ and $\beta$ values for diesel fuels and bio-diesel fuels at $T_S=352^\circ$C and $T_S=308^\circ$C

### 6.3.2 Deposit composition

Figure 6-9 shows the absolute masses of deposit composition for diesel fuels and bio-diesel fuels. Due to a lack of samples, the composition of B100 deposits is not provided in the figure. Subdivided samples of DFP were due to a relatively large amount of a mound-like deposit accumulating on the hot surface at the end of the deposition. According to Caceres, et. al. [7], combustion chamber deposits exist in two major layers which have different structures. As shown in the figure, the samples were separately classified as upper and bottom parts to observe the composition differences at different parts of the deposits. However, there was no
apparent difference between the compositions of upper and bottom parts of the deposits. This means that the deposits obtained had homogeneous compositions.

![Deposit composition diagram]

**Figure 6-9** Absolute deposit composition masses

Based on the figure, in general, soot masses were proportional to the total mass of deposit samples. All deposit samples obtained soot masses of almost 50% from their total masses except for the deposit sample for B100C at $T_s=352^\circ\text{C}$ that obtained soot masses less than 2% from the total mass. For B100C at $T_s=352^\circ\text{C}$, most of the carbonaceous deposits changed into white matter as can be seen in **Figure 6-7**(D) which contained more sulfate and other material components such as ash around 14% and 75% in average, respectively.

There were no clear differences between sulfate and SOF components. However, we believe that the amount of SOF in the deposits strongly depended on the amount of deposits accumulated on the hot surface, deposit structures (porosity) and overlapping condition between the droplet impingement interval and droplet lifetime. A large amount of deposits with high porosity would obtain a greater amount of SOF in deposits, due to the ability of the deposits to absorb and trap liquid fuel when an overlapping condition occurred.

### 6.3.3 Deposit formation mechanism

The fluctuation of deposit surface temperatures was caused by competition among the cooling effect, surface oxidation effect and heat transfer effect during
deposit formation. The domination of the cooling effect, surface oxidation effect and heat transfer effect during deposit formation are indicated by regions A, B and C in Figure 5-8 (Chapter 5), respectively. It is important to mention here that surface oxidation involves the thermal oxidation of liquid fuel and the oxidation of carbonaceous deposits. Droplet lifetime in the figure was estimated by the surface temperature of deposits and the evaporation characteristics obtained by the evaporation test.

Generally, for the rapid development of deposits, the deposit surface temperature tended to be lower than the hot surface temperature (region A and C in Figure 5-8) and its initial droplet lifetime was not maintained where an overlapping condition existed, as shown by the result obtained for B100 in Figure 5-8. However, for slow development of deposits as shown by the DF results in the figure, the deposit surface temperature tended to be maintained close to the hot surface temperature (region B in Figure 5-8). Its initial droplet lifetime was kept nearly constant where a non-overlapping condition was completely maintained.

For B100, a cooling effect by liquid fuel was dominant at the beginning of deposition. It reduced the surface temperature. Then, the effect of surface oxidation took place after the repetition number increased, where heat was released and resulted in an increase of the deposit surface temperature. After more deposits accumulated, the deposit surface temperature kept decreasing due to the effect of low thermal conductivity of deposits (region C in Figure 5-8). The effect of low thermal conductivity of the deposit layer was greater than the oxidation effect. An overlapping condition was observed during this deposition, with an increase in droplet lifetime for a greater number of repetitions.

For DF, however, only a slight increase in deposit surface temperature was observed, where its maximum temperature was within the hot surface temperature fluctuation. Non-overlapping conditions occurred until the end of repetitions. Due to a lesser amount of deposits with layer-like features, a cooling effect at the beginning stage and the effect of surface oxidation during the later stage were more dominant for this slow deposit development. There was a minimum effect of thermal conductivity of deposits.

B100C deposit surface temperature in Figure 6-10 and 6-11 show that both deposit surface temperature profiles tended to be maintained throughout the deposition. Further, their maximum deposit surface temperature increased to a constant value that was far higher than the hot surface temperature.

A higher deposit surface temperature resulted in a shorter evaporation lifetime and a more increasing non-overlapping tendency throughout the deposition. This
was probably caused by the slow oxidation of the deposit layer and also the effect of a thin deposit layer at the impingement point. The above reasons and actual observation during deposition showed that the droplet lifetime estimation shown in **Figure 6-10** was not appropriate in estimating droplet lifetime during deposition for the test condition within the transition boiling regime.

**Figure 6-10** B100C deposit surface temperature fluctuation at $T_S=352^\circ C$

A deposit surface temperature higher than the hot surface temperature might give disadvantages for B100C, where for real engine knocking might occur [6, 102].

In terms of the deposit surface temperature, the result for DFP was obviously different from DF as shown in **Figure 6-12**. The DFP deposit surface temperature was high at the beginning of deposition and reduced below the hot surface temperature after the repetition number increased. 1% B100C in DFP might contribute to this result.

Clearly from the droplet lifetime estimation, heat transfer through deposits altered the fuel droplet lifetime and overlapping condition, thus effecting the formation of fuel deposits. The initial condition could not be maintained throughout the deposit formation.

Deposit formation depended on various factors and relies not only on fuel properties as shown in the results for DFP and B100C at 352°C. The evaporation
of DFP droplets within the nucleate boiling regime caused a greater amount of deposits accumulated at the initial stage compared to B100C that evaporated within the transition regime at the initial stage of deposition.

**Figure 6-11** B100C deposit surface temperature fluctuation at $T_s=308^\circ$C

![Image of Figure 6-11](image1)

**Figure 6-12** DFP deposit surface temperature fluctuation

![Image of Figure 6-12](image2)
A greater formation of deposits for DFP at the initial stage caused deposit surface temperatures to reduce when the repetition number increased. Thus, this increased the development of the DFP deposits. Due to a formation of less deposits and the greater effect of oxidation for B100C, the deposit surface temperature was maintained, exceeding the wall surface temperature that caused slow deposit development. Furthermore, the value of T90 for B100C was lower than DFP.

Hot surface temperature, an overlapping condition between impingement interval and droplet lifetime, fuels, deposit properties, initial stages of deposition and competition phenomena during deposit formation are factors influencing deposit formation and its development in this study.

6.4 Summary

Deposition characteristics in terms of deposit developments, deposit compositions and deposit surface temperature fluctuation for different types of diesel fuels and bio-diesel fuels were discussed. These characteristics may help to obtain a better understanding of deposit formation, especially for bio-diesel fuels. The main results are summarized as follows:

1. The fuel evaporation characteristics provided information about the initial wetting condition, droplet physical interaction with the hot surface and droplet lifetime estimation during deposition that can be used to explain deposit formation on the hot surface.
2. The initial stage of deposition was much affected by droplet-surface interaction and deposit formation from fuel at certain surface conditions. More deposits accumulated at the initial stage of the deposition that occurred within the nucleate boiling regime. In this state, a greater contact area resulted from the impingement of droplets on the hot surface.
3. Coconut oil methyl ester based bio-diesel fuel (B100C) obtained lower deposit development compared to palm oil methyl ester based bio-diesel fuel (B100) due to its lower maximum evaporation rate point and shorter evaporation lifetime. Thus, B100C had advantages over B100 in reducing deposit formation tendencies in engines.
4. The formation of coconut oil bio-diesel fuel deposits caused the deposit surface temperature that exceeded the wall surface temperature. This might cause some problems such as engine knock in a real engine.
5. The B100C content in DFP had a significant effect on increased values of fuel properties such as density, T90 and droplet lifetime higher than the values of DF. Due to these reasons, DFP obtained a higher tendency toward deposit formation compared to DF.
Chapter 7

Conclusions

A repetition test of single droplet evaporation was developed for the fundamental research of fuel deposition. In HSDT (hot surface deposition test), a single droplet that was repeatedly impinged on the hot surface, evaporated and some of the fuel components were slowly oxidized and changed to carbonaceous deposits. In the test, over 5,000 repetitions of droplet evaporation were attained to obtain the development of deposits. From this study, we have drawn the following conclusions:

(1) The hot surface deposition test (HSDT) was capable of obtaining results similar to the engine deposition test (EDT) in terms of deposit development and soot fraction in deposits. Furthermore, the test conditions for HSDT are similar to some real diesel engine conditions such as wall surface temperature, wetting condition, heat transfer boiling regime and part of deposit mechanisms. Thus, a single droplet repetition apparatus could be used to estimate deposit development in a real engine. Deposit development characteristics obtained in this study showed that HSDT has a great potential to differentiate deposit development for various types of fuels. The deposit development on the hot surface in HSDT can be used to simulate part of the deposition in a real engine, especially for deposit formation on a hot wall in a combustion chamber due to fuel impingements. To improve the study, other mechanisms not included in this study, such as the components of combustion products and impaction factors during deposit formation as mentioned by Lepperhoff, et. al. [26], should be involved during deposit formation on a hot wall. Further, it is more beneficial if the simplified deposition test can involve high temperature gas and a high pressure environment similar to an engine. However, to produce these conditions some difficulties may be encountered, but it is not impossible to achieve them.

HSDT is considered an initial step in developing a simplified method for investigating deposit development in an engine. The test can describe more precisely the real engine deposit formation if similar deposit mechanisms and conditions for real engines are applied.

(2) In this study, the deposit formation rate ($\beta$) and the initial amount of deposit described by coefficient $\alpha$ were quantitatively evaluated. The deposit formation
process can be expressed using the following equation:

\[
\frac{M_r}{m_D} = \alpha N_D^\beta \quad \text{for HSDT and} \quad \frac{M_r}{m_{nj}} = \alpha N_{nj}^\beta \quad \text{for EDT.}
\]

Both equations have similar physical meanings that make the equations usable to compare the value of \(\alpha\) and \(\beta\) for the simplified test with the value of \(\alpha\) and \(\beta\) obtained for the real engine.

The equation of deposit development introduced in this study can describe deposit development for both simplified and real engine deposition tests. The equation used for HSDT describes well the deposit development for different tested fuels in real engine deposition tests.

(3) An explanation of the various results in this study can be made, when the deposition characteristics is coupled with the evaporation characteristics. The fuel evaporation characteristics provided information about the initial wetting condition, droplet physical interaction with the hot surface, and droplet lifetime estimation during deposition that can be used to explain deposit formation on the hot surface. The reasons for deposit development, deposit features, droplet lifetime fluctuation and competition phenomena can be understood and explained clearly. In this study, the evaporation test was conducted on a clean metal surface. The evaporation characteristics on hot surface similar to the deposit material surface might help in obtaining more realistic results and observation of fuel evaporation on the deposit layer. The fuel droplet evaporation on deposit surface is significant for more realistic explanation, where, to our knowledge, this information is still not available in recent literature.

Deposition and evaporation characteristics for different types of fuels obtained in this study are significant for explaining the deposition result obtained for HSDT.

(4) The effect of temperature and a wet/dry condition of a hot surface on fuel droplet deposition was investigated. The hot surface temperature affected deposit formation. MEP (maximum evaporation rate point) observed in the evaporation lifetime diagram of a single droplet was the key temperature for deposition development. Different sub-cooled temperatures from the MEP temperature showed different droplet-surface interaction, evaporation lifetime and wet/dry conditions where various deposit development features resulted. The non-overlapping and dry deposit condition result in less total amount of deposit described as slow deposit development. For deposition of DF (Diesel fuel: JIS
No. 2) at various surface temperatures, there are two types of deposit developments; (1) two-stage development for surface temperatures lower than the MEP temperature, and (2) single-stage development for surface temperatures close to the MEP temperature. The hot surface temperatures located near MEP temperature (small sub-cooled temperature) have the potential of reducing deposit formation on the hot surface. In this study, the amount of deposit accumulated for surface temperatures far lower than the MEP temperature (sub-cooled temperature of -30°C), can be reduced up to approximately 55% when the surface temperature is increased closer to the MEP temperature (sub-cooled temperature of -5°C). More deposit reduction can be obtained when the surface temperature is higher than the MEP temperature (sub-cooled temperature of 10°C) due to the deposition within the transition boiling regime. At that temperature, approximately 70% deposit reduction could be obtained. However, depositions within this regime have slightly higher deposit development rate due to longer evaporation lifetime. Decreased non-volatile fuel remains, the existence of non-overlapping and dry deposit conditions, higher deposit surface temperatures and higher oxidation rate of carbonaceous deposits were factors contributing to deposit formation reduction within the temperature regime close to the MEP temperature.

The hot surface temperature is an important factor in deposit development on a hot surface, where it can be manipulated to reduce deposit formation in an engine. Surface temperatures close to the MEP temperature have clear tendencies to obtain slow deposit development with less accumulated deposits.

(5) The impingement interval and surface temperature determine the initial non-overlapping and wet/dry conditions. The impingement interval longer than a droplet lifetime is significant for the existence of non-overlapping conditions. But for a dry deposit conditions, the condition can be maintained when the impingement interval is long enough to make sure the non-volatile fuel components remaining on the hot surface are completely transformed into deposits. In contrast with non-overlapping and dry deposit conditions, overlapping conditions exist only when the impingement interval is shorter than the droplet lifetime. Generally, the overlapping and wet dry conditions are co-existent. However, the effect of the deposit is another factor for the wet/dry condition at a later stage of deposition. The non-overlapping and dry deposit condition results in fewer deposits. For the overlapping and wet deposit conditions, the accumulation of more total deposits resulted. According to the results obtained
for the surface temperature effect on deposition, for a short impingement interval \( (\tau_{\text{imp}} = 5 \text{sec}) \), a surface temperature close to the MEP temperature \( (T_S = 352^\circ \text{C with } 5^\circ \text{C difference from MEP}) \) experienced non-overlapping and dry deposit conditions. However, surface temperatures far lower than the MEP temperature \( (T_S = 270^\circ \text{C with } 87^\circ \text{C difference from MEP}) \) obtained continuous overlapping and wet deposit conditions. At the later stage of deposition for both types of conditions, the amount of deposit accumulated for the temperature close to MEP can be reduced up to 97% from the amount of deposit accumulated for a surface temperature far lower than MEP.

The existence of non-overlapping and dry deposit conditions was preferable to reduce deposit formation on a hot surface.

(6) Deposition characteristics in terms of deposit developments, deposit compositions and deposit surface temperature fluctuation for different types of diesel fuels and bio-diesel fuels were discussed. These characteristics may help to obtain a better understanding of deposit formation, especially for bio-diesel fuels. HSDT indicated that palm oil based methyl ester bio-diesel fuel (B100) and its blends (B50, B20, B5) had some risk of engine deposits under wet surface conditions but the deposition development rate depended on the blend ratio. The wet condition was not the main reason for rapid development of deposits but enhanced the deposit accumulation. In this study, it was not certain that a higher blend ratio will produce more deposit at the initial stage of deposition. However, for a later stage of deposition, the blend ratio probably is one of the main factors in determining the deposit development rate and the total amount of deposit accumulated.

HSDT indicated that bio-blended fuel had some risk of engine deposits under wet surface conditions but the deposition development rate depended on the blend ratio.

(7) Coconut oil methyl ester based bio-diesel fuel (B100C) obtained lower deposit development compared to palm oil methyl ester based bio-diesel fuel (B100) although the test condition was changed. This was due to its lower maximum evaporation rate point and shorter evaporation lifetime compared to B100. At 9,000 repetitions, the different test conditions for B100C obtained approximately 91% to 95% less deposit accumulated compared to B100. Thus, B100C had advantages over B100 in reducing deposit formation tendencies in engines. The formation of coconut oil bio-diesel fuel deposits caused the deposit surface
temperature that exceeded the wall surface temperature. This might cause some problems such as engine knock in a real engine. The B100C content in DFP had a significant effect on increased values of fuel properties such as density, T90 and a droplet lifetime higher than the values of DF. Due to these reasons, DFP obtained a higher tendency toward deposit formation compared to DF. DFP obtained rapid development of deposit with $\beta=0.75$ and slow development of deposit for DF with $\beta=0.29$. Due to the large difference between the development rate for DFP and DF, the condition of the amount of deposit accumulated for DFP that was far greater than DF will continue although at longer repetition numbers.

B100C has advantages over B100 in terms of less deposit accumulation, but the effect of B100C blends with DF need further investigation.

(8) The deposit mechanism in this study was described according to the fluctuation of deposit surface temperature and the fluctuation of droplet lifetime during the deposition process. The fluctuation of deposit surface temperature was caused by competition among the cooling effect, surface oxidation effect, and heat transfer effect during deposit formation. Generally for the rapid development of deposits, the deposit surface temperature tended to be lower than the hot surface temperature at the initial stage of deposition and its initial evaporation lifetime was not maintained where an overlapping condition existed. A cooling effect by liquid fuel was dominant at the beginning of deposition and reduced the surface temperature. Next, surface oxidation took part after the repetition number increased, where heat was released, resulting in an increase in the deposit surface temperature. After more deposits accumulated, the deposit surface temperature decreased due to the effect of low thermal conductivity of deposits. The effect of low thermal conductivity was greater than the oxidation effect. An overlapping condition with an increasing evaporation lifetime was observed during this deposition domain. However, for the slow development of deposits, a non-overlapping condition was maintained from the beginning to the end of the deposition experiment. Due to a fewer amount of deposits, the cooling effect at the beginning and surface oxidation during the later stage were dominant factors for slow deposit development. There was a minimum effect of thermal conductivity on deposit surface temperature.

Deposit formation in this study also depends on the competition phenomena between the cooling effect, oxidation effect and heat transfer effect (thermal conductivity of deposits) during the deposition process.
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