DEVELOPMENT OF BIO-BASED 2T ENGINE OIL IN MARINE ENGINE APPLICATION

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RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2020

UNIVERSITY OF MALAYA

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ABSTRACT

Two-stroke engines are a simple and lightweight two-cycle spark ignition engine with no oil sump is needed. The use of bio-based lubricants was analyzed to replace commercial mineral and synthetic-based lubricants. Lubricants were prepared by mixing three components of oil which comprise of base oil, additives, and solvent. In this research, four samples of base oil had been prepared with a different weight ratio of the PFAD-NPG ester and Type II mineral. Then each of the samples were added with a similar weight ratio of additives and solvent. A commercial lubricant was used as a reference lubricant to be compared with samples prepared. A viscometer was used to determine the viscosity index and density of each sample and reference lubricant. Next, a four-ball tribo-tester was used to evaluate friction and wear prevention characteristics in each sample and reference lubricant. Finally, an idle operation mode had been conducted on a two-stroke brush cutter engine to determine the effect of reference lubricant and bio-based lubricant towards carbon deposition on the spark plug. Lubricant sample B comprises a 40% weight percentage of PFAD-NPG ester and a 60% weight percentage of Type II mineral oil. Sample B had exhibited the highest viscosity index of 154.4 compared to other samples and reference lubricants with the lowest viscosity index of 129.5. This enables it to form a thick lubrication film between moving surfaces. Based on friction evaluation results, it can be seen that Sample B has recorded the lowest COF value compared to reference lubricant. Through the WSD analysis conducted, sample B was recorded to have the lowest WSD value which is 580.69mm compared to the reference lubricant which is 794.35mm. Sample B caused the least wear on the three lower ball bearings used in the tribo-tester experiment. For the engine performance test, sample B has undergone complete combustion with fuel without leaving any carbon deposits on electrodes and insulator tips. In conclusion, the bio-based lubricant has improved engine efficiency and reduce wear in a two-stroke engine.

Keyword: Friction, Viscosity Index, WSD, Carbon Deposits, Density

PERKEMBANGAN MINYAK 2T BERASASKAN BIO DALAM APLIKASI ENGINE MARINE

ABSTRAK

Enjin dua lejang adalah mesin pencucuh percikan dua kitaran yang ringan dan mudah dikendalikan tanpa memerlukan kotak engkol yang terasing daripada kebuk pembakaran. Penggunaan pelincir berasaskan bio telah dianalisiskan untuk menggantikan pelincir asas mineral dan sintetik komersial. Pelincir disediakan dengan mencampurkan tiga komponen minyak yang terdiri daripada minyak asas, bahan tambahan dan pelarut. Dalam penyelidikan ini, empat sampel minyak asas telah disediakan dengan nisbah berat ester PFAD-NPG dan mineral Type II yang berbeza. Kemudian setiap sampel ditambahkan dengan nisbah berat bahan tambahan dan pelarut yang serupa. Pelincir komersial digunakan sebagai pelincir rujukan untuk dibandingkan dengan sampel yang disediakan. Viskometer digunakan untuk menentukan indeks kelikatan dan ketumpatan setiap sampel dan pelincir rujukan. Seterusnya four ball tribo-tester bola telah digunakan untuk menilai ciri-ciri pencegahan geseran dan keausan bagi setiap sampel dan pelincir rujukan. Akhirnya, mod operasi ideal telah dijalankan pada mesin pemotong rumput dua lejang untuk menentukan akibat pengunaan pelincir berasaskan bio dan pelincir rujukan terhadap pemendapan karbon pada palam pencucuh. Sampel pelincir B yang terdiri daripada 40% peratusan berat PFAD-NPG ester dan 60% peratusan Type II mineral Sampel B telah menunjukkan indeks kelikatan tertinggi 154.4 berbanding sampel-sampel yann lain dan pelincir rujukan dengan indeks kelikatan terendah 129.5. Ini membolehkannya membentuk filem pelincir tebal di antara permukaan yang bergerak. Berdasarkan hasil penilaian geseran, dapat dilihat bahawa Sampel B telah mencatat nilai COF terendah berbanding pelincir rujukan. Melalui analisis WSD yang dilakukan, sampel B dicatatkan mempunyai nilai WSD terendah iaitu 580.69mm berbanding pelincir rujukan iaitu 794.35mm. Sampel B telah diperhatikan menyebabkan paling sedikit haus pada tiga galas bebola bawah yang digunakan dalam eksperimen tribo-tester. Untuk ujian prestasi enjin, sampel B telah mengalami pembakaran lengkap dengan bahan bakar tanpa meninggalkan deposit karbon pada elektrod dan petua penebat. Kesimpulannya pelincir berasaskan bio telah meningkatkan kecekapan mesin dan mengurangkan keausan pada mesin dua lejang.

Kata Kunci: Geseran, Indeks Kelikatan, WSD, Pemendapan Karbon, Ketumpatan

ACKNOWLEDGEMENTS

Firstly, I would like to thank and show my appreciation to my supervisor, Dr. Nurin Wahidah Binti Mohd Zulkifli for guidance and advice to carry out my research project successfully. I would also like to show my gratitude to MR. Muhammad Syahir Amzar bin Zulkifli for his guidance and support during experiments carried out throughout this entire research project.

Next, I would like to thank my parents for giving full support and encouragement during the difficult times of handling research project reports and full-time work at the office. I would also like to show my sincere appreciation to my course mates for their kindness in helping me out when their guidance is needed.

I also would like to offer my regards and thankfulness to the staffs and lecturers of the Faculty of Engineering of University Malaya for their encouragement and support.

Lastly, I would like to thank the almighty God for all his blessings and wisdom given to me to carry out this research project and complete it successfully.

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LIST OF SYMBOLS AND ABBREVIATIONS

PFAD	:	Palm fatty- acid distillate
NPG	:	Neopentyl glycol
2T engine	:	Two-stroke engine
VI	:	Viscosity index
COF	:	Coefficient of friction
WSD	:	Wear scar diameter
API	:	American Petroleum Institute
HC	:	Hydrocarbon
PAO	:	Polyalphaolefin
CO	:	Carbon monoxide
CO_2	:	Carbon dioxide
O_2	:	Oxygen
PIB	:	Polyisobutylene
AO	:	Anti-oxidant
AW	:	Anti-wear
GO	:	Graphene oxide
ZDDP	:	Zincdialkydithiophosphate
EP	:	Extreme pressure
RON	:	Research octane number
AF	:	Anti-foam agents
PM	:	Particulate matters
POA	:	Primary organic aerosol
SOA	:	Secondary organic aerosol

CNG	:	Compressed natural gas
LPG	:	Liquified petroleum gad
DI	:	Direct injector
FA	:	Fatty acid
TMTPO	:	Trimethyl propane trioleate
ASTM	:	American society for testing and materials
SAE	:	Society of automotive engineering
TO	:	Base oil
RL	:	Reference Lubricant

CHAPTER 1: INTRODUCTION

1.1 Background

In marine nor in many other industries which comprises engines and hydraulic maneuvering, a lubricant is widely being used. It minimizes friction caused by moving surfaces in connection. Lubricant act as a friction-reducing film between surfaces and dissipates heat produced during motion. Besides that, it also helps to prevent wear and tear of the surfaces, avert corrosion, transmit forces, and power or control temperatures of surfaces. Lubricity is commonly known as the property of reducing friction. Engine performance might drop, the engine shelf life may reduce, and the maintenance cost of the engine may rise if the lubricity level is unsatisfactory. A lubricant can be solid, liquid or plastics depend on its needs in the industry. Liquid lubricant is widely used in automotive engines. In this research, the development of lubricants for the two-stroke engine in the marine industry applications will be discussed further. Two-stroke engines differ with four-stroke engines by having a higher power to engine weight ratio. This advantage enables it to be used in small applications such as lawnmower, motorbikes, leaf blowers, and more. It does not require an oil sump such as four-stroke engines. Therefore, a two-stroke engine requires the lubricant to ensure the engine is maintained clean and friction is minimized within it. The lubricant used in the two-stroke engine is known as two-stroke oil which comprises base oil, additive package, and solvent. Unlike the four-stroke oil, two-stroke oil is premixed with fuel in the combustion chamber and emission of the exhaust will take place (Zulfattah et al., 2019). Therefore, the probability of using a bio-based lubricant is being studied and reviewed in two-stroke engine oil.

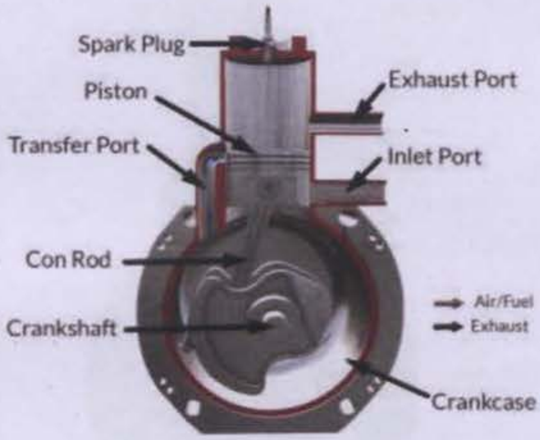


Figure 1.1: Two-stroke engine components (JOHN, 2019)

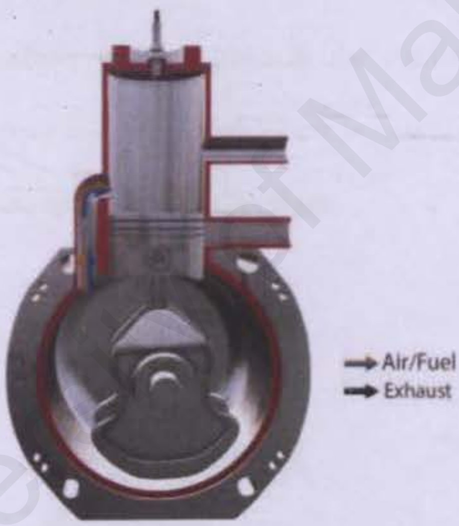


Figure 1.2: Two-stroke engine suction (JOHN, 2019)

During this suction stage, the piston moves towards the bottom of the crankshaft whereby the air-fuel mixture is compressed within the crankcase and the transfer port is opened. Then the compressed air-fuel mixture flows to the combustion chamber from the crankcase as soon the transfer port opened. When the piston moves towards the combustion space, it will close the transfer port whereby the inlet port begins to open and the air-fuel mixture will begin to flow into the crankcase.

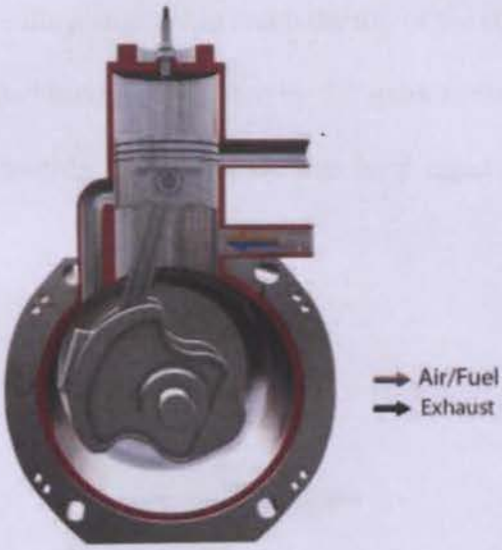


Figure 1.3: Two-stroke engine compression stage (JOHN, 2019)

While the piston continues to move towards combustion space, it covers the exhaust port. As the piston continuously moving towards the combustion space the air-fuel mixture in the combustion space is compressed. There is a significant rise in pressure and temperature in the combustion space during this stage.

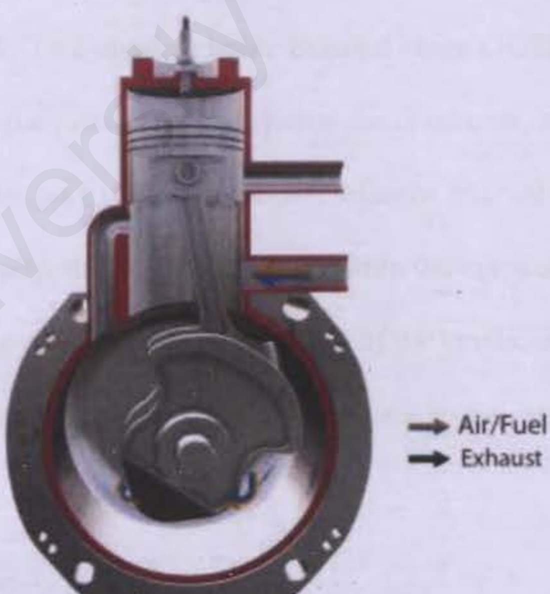


Figure 1.4: Two-stroke engine ignition stage (JOHN, 2019)

At this stage, right before the piston could reach the top of the combustion space ignition takes into place. The air-fuel mixture is ignited by the spark from a spark plug. The piston is then forced to push towards the crankcase due to a rapid rise in temperature and pressure.

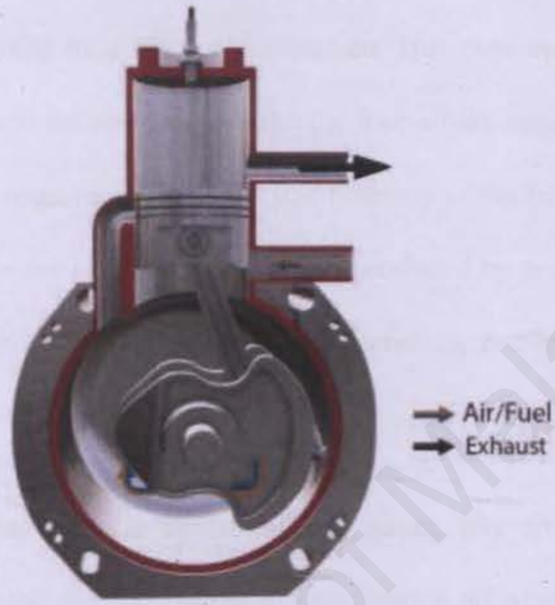


Figure 1.5: Two-stroke engine exhaust stage (JOHN, 2019)

In these stages, when the piston moves towards the crankcase, two mechanism takes place. Firstly, the exhaust port is uncovered and exhaust gas will expel out from the combustion space. Secondly, the air-fuel mixture within the crankcase is compressed by the moving piston. As the piston reaches the bottom of the crankcase, the transfer port is opened and the compressed air-fuel mixture flows back to the combustion space. The cycle then repeats.

1.2 Problem Statement

Approximately 30 to 40 million tons of lubricants is being used yearly to accommodate high energy demand around the globe. The main constituent of these lubricants is engine oil. Two-stroke engines produce a greater power to weight ratio, simple in their construction and easy maintenance. These advantages make the two-stroke engine become a perfect choice in a marine application. However current two-stroke engine emits more pollutants to the sea compared to the four-stroke engine. A two-stroke engine requires a two-stroke engine oil due to the low lubricity of the fuel. Presently, most of the two-stroke engine oils are petroleum-based and produced by petroleum companies. Due to its high toxicity and non-renewability characteristics, two-stroke engine oils pose a great risk to the environment.

These oils also contribute to environmental issues, like air pollution caused when combustion of engine oil and the leaking of toxic engine oil which harm the water bodies from sea, river, and lake. Besides that, the burning of premixed two-stroke lubricants and fuel together in the combustion space emits more smoke, carbon monoxide, particulate matter, and hydrocarbon to the environment. In an engine, the friction causes parasitic loss which can reduce the engine's overall efficiency that leads to incomplete fuel combustion. The major contribution of friction in an engine comes from the interaction of the piston and cylinder wall. Therefore, lubricants play a vital role in heat dissipation and reduce friction within the engine. Thus, application of a highly biodegradable with less toxicity feedstock such as PFAD-NPG ester is essential in the preparation of bio-based lubricant oil for a two-stroke engine to ensure the sea and surrounding area not polluted by the emission of the two-stroke engine.

This research focuses on the development of bio-based two-stroke oil for a two-stroke engine application that benefits the fishermen and small boat users.

1.3 Objectives

Following are the objectives of this study:

i. To determine the tribological and physiochemical properties of 2T bio-based lubricant blends and commercial mineral lubricants.

ii. To analyze the effects of mixtures in lubricant samples which comprises different weight ratio PFAD-NPG esters and Type II mineral as base oils, additive packages, and D80N solvent on the carbon deposition.

1.4 Scope of Research

The main purpose of this investigation is to determine the tribological and physicochemical properties in the formulation of two-stroke engine oil. PFAD-NPG ester and Type II mineral have been chosen as base oils. Additive packages comprised of GO, AO, PIB 1300, PIB 1100, and ZDDP were added to the base oils. A few samples comprising of base oil, additive package, and solvent which vary in ratio have been mixed. Based on the samples prepared, the optimum mixing ratio is determined to obtain the lowest friction and wear losses when the piston-cylinder is in linear movement. The tribological properties of the new lubricant are evaluated by carrying out an experiment using a Tribotester machine. Engine performance tests to be carried out to determine the spark plug carbon deposition.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

There are many types of research that have been carried out on the formulation of engine lubricants to reduce parasitic losses caused by friction and improve engine efficiency. However, most researches were done for four-stroke engine oil, unlike two-stroke engine oil which is still being widely used in marine engine application. The capability of lubricant to enhance tribological properties solely depends on the effectiveness in the formulation of the lubricant itself (Panchal, Patel, Chauhan, Thomas, & Patel, 2017). As for the two-stroke engine, the burning of mixed fuel and lubricants that takes place in the combustion chamber will produce emissions products through the exhaust port. In this chapter, studies on improving tribological properties of lubricant mainly in reducing friction and wear on the engine mechanism will be reviewed.

2.2 Compositions of Lubricants in Two Strokes

Firstly, it is essential to know what are the compositions of engine lubricants so that environmental pollution caused by vehicles and machine emissions can be reduced. The base oil resources of the lubricants are categorized into three categories which comprise natural oil, refined oil, and synthetic oil. Most major industries such as automobiles, factories, and food industries use these lubricants in their machinery to prevent friction and wear. However, all these three categories of base oils differ by their characteristics and application. Refined oils are obtained from crude or petroleum reserves which are commonly used in most industries. Synthetic oil is synthesized from the end product of a chemical reaction that is formulated based on needs. Finally, natural oil is derived from animal fats and vegetables (Singh, Farooq, Raza, Mahmood, & Jain, 2017). Recent researches have shown that natural oil is a favorable base oil to be used because of its environmentally friendly properties.

Mineral oil, semi-synthetic oil, and fully synthetic oils are the oils used as two-stroke engine lubricants for marine engine applications. Mineral oils/refined oils are made from crude oil or in earlier years was derived from natural oil. Semi-syntactic oil is classified as API group 3 base oil. Group 3 base oils achieve a saturation above 90%, almost a removal of Sulphur less than 0.03%, and an SAE viscosity index above 120. Group 3 base oils are severely hydrocracked at a higher temperature and pressure to produce purer base oil (Adhvaryu, Erhan, Sahoo, & Singh, 2002). Fully-Synthetic oil is a chemically synthesized base oil with no mineral oil present which makes it more expensive compared to other base oils. Different compositions of oil will produce a different combustion rate in an engine. Therefore, different types of base oil will give different lubricating characteristics. It will also influence the combustion of fuel to produce higher power and greater performance of the engine.

Vehicle emission is one of the major contributors to environmental pollution, especially by two-stroke engines. Pollutants which comprises of particulate matter (PM) and hydrocarbon are certainly harmful. They contained and spread around the environment whereby people carry out their daily activities. Studies have shown that a two-stroke engine emits 10 times more PM comparatively to a four-stroke engine. This is due to the lubricating oil is mixed with fuel and burned together in combustion space while the gases are exchanged via ports located at the cylinder. A minor quantity of fresh air and fuel also escapes together with exhaust gas when both intake and exhaust port are open. Thus, the exhaust contains a high level of unburned fuel and lubricant which ease further environmental pollution (Begum, Biswas, & Hopke, 2006).

Particle matters (PM) can be further classified into black carbon, primary organic aerosol (POA), secondary organic aerosol (SOA). Two-stroke engine vehicle such as scooters is found to produce asymmetric pollution which able to dominate urban pollution in Asia compared to diesel vehicles (Platt et al., 2014). As a result, some of the Asian countries have completely replaced their two-stroke engines to compressed natural gas (CNG)-powered four-stroke engines in their vehicles. For instance, in Dhaka, Bangladesh, CNG powered cars and three-wheelers have been introduced lately. A remarkable decrease of 40% in their PM concentration have shown through their research done. This is due to the policy of the Bangladesh government in restricting the two-stroke engine and replacing it with a CNG-powered four-stroke engine in their vehicles (Begum et al., 2006). Likewise, in India, modern auto rickshaws have been converted to CNG or LPG powered four-stroke engines due to government regulation and environmental awareness.

Besides having a high emission of hydrocarbon, the two-stroke engine also has higher heat flux in the combustion chamber causing increased heat losses. Misfires do happen at low speed in the two-stroke engine due to poor scavenging systems aside from having incomplete combustion. The wear and tear of the two-stroke engine are greater due to the poor lubrication system. Up to date, most researches done have shown more the negative impact on the two-stroke engine due to their association with heavy pollution. However, it cannot be justified that all these issues alone are inborn to the two-stroke engine concept. For example, an improved two-stroke engine has a better lubrication system comparatively to cheap, simple, and small two-stroke engines. Likewise, in the early 90s Toyota have developed a prototype of converting a two-stroke engine from a four-stroke engine.

It was done by using poppet valves as scavenging port and by boosting the engine via root compressor. Comparatively to previous diesel engines, Toyota manages to rise both power and torque by 20% and 40% respectively besides reducing the emission (Mattarelli, Cantore, & Alberto, 2013). With such advances in technology, the performance of combustion is also significantly improved. Therefore, a two-stroke engine stands a chance over the four-stroke engine due to its remarkable power to weight ratio and simple build-up.

In recent research to increase the power performance and fuel efficiency, a boosted uniflow scavenged direct injection gasoline (BUSDIG) two-stroke engine was developed. A uniflow scavenge method was used to improve scavenging performance and reduce charge short-circuiting phenomenon. An exhaust valve and air transfer valve were added on the cylinder head. Then, a direct injector (DI) and a spark plug were fixed at the center of the engine. This improvement on the two-stroke engine eliminates fuel short-circuiting when the scavenge port and exhaust valves are closed. Besides that, spark-assisted combustion is lean combustion via low-temperature combustion mode which allows a two-stroke engine to have high efficiency and low emission. As a result, the environmental pollution caused by the emission of the two-stroke engine can be eliminated (Wang & Zhao, 2019).

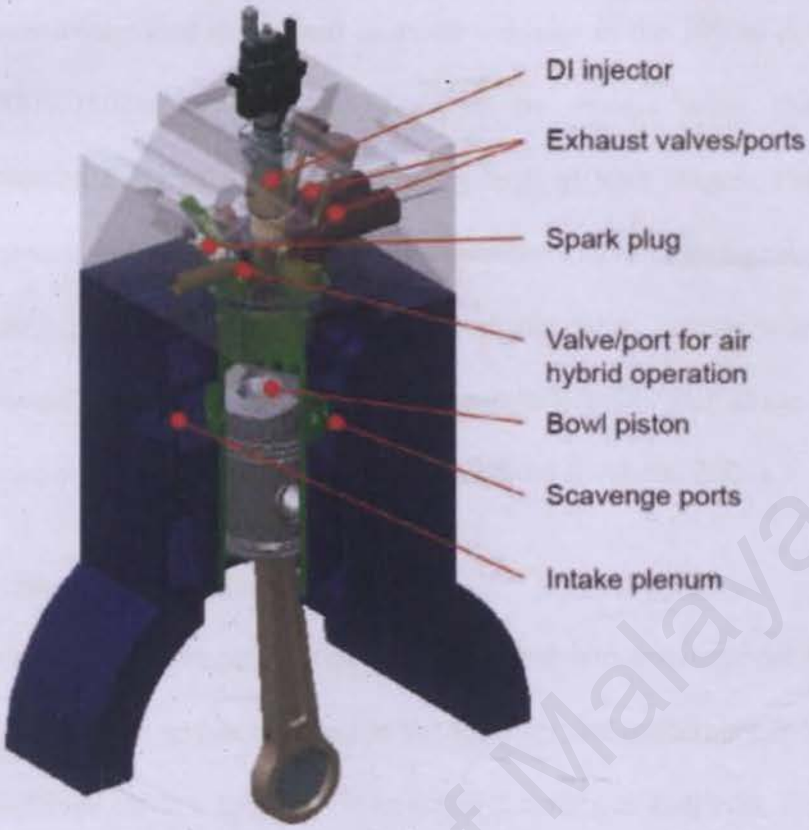


Figure 2.1: Design of the BUSDIG engine

A similar advancement has been introduced in TVS 50, a bike from India which uses direct injection (DI) technology to reduce emission and improve fuel efficiency. A prototype has been designed to retrofit the existing carbureted engine to a DI two-stroke engine. The fuel is directly introduced to combustion space through an injector fixed at the top of the cylinder head. This enhancement allows the exhaust product to be scavenged out from the cylinder by using air. This process ensures the reduction in unburned fuel amount that escapes during scavenging unlikely in a carbureted two-stroke engine. Studies have shown that this improved technology has significantly reduced carbon monoxide emission by 72% and unburned hydrocarbon emission by 80% while annihilating visible exhaust smoke. Besides improving complete combustion and reducing short-circuiting loses, this modified two-stroke engine has shown a 32% the increase in fuel efficiency compared to existing carbureted engine (P.Sanjaikumar, 2013)

Whereas in Europe, the air-assisted direct injection system widely used in the marine industry and was improvised to be used in motor vehicles in the 1990s. A well-known two-stroke DITECH,50cc scooter was designed by Aprilia using this advanced technology whereby Peugeot and Piaggio adapt to it at later stages. This is due to European regulations where motor vehicle manufacturers have to stringently follow the Euro 1 and Euro 2 emissions standard. The European 50cc, scooter market is fully utilizing the air-assisted direct injection engine due to its benefits such as the annihilation of exhaust smoke and misfire-free combustion (Leighton & Ahern, 2003).

2.2.1 Base Oil

The base oil for lubricants can be categorized further into conventional base oil and bio-based oil which is widely being used in the vehicles and machinery industries. The main purpose of base oil in a lubricant is to act as a carrier to additives. Base oils also must be able to keep the additives within the lubricant under normal working conditions besides removing heat and eliminating wear between moving surfaces.

2.2.1.1 Conventional Base Oil

The conventional base oil is refined from crude oil petroleum (mineral oil) or through chemical synthesis (synthetic oil). Base oil that is made from crude oil consists of hydrogen atoms and 18 to 40 carbon atoms which have a boiling point that ranges from 280°C to 570°C. This hydrocarbon compound can be classified into paraffin, olefins, naphthenes, and aromatics depending on their chemical molecular structure (Prince, 1997). Meanwhile, synthetic oil is produced artificially to replace mineral oil with enhanced superior properties. This enables synthetic oil to be used at high temperatures or low temperatures depend on machinery or engines application (S & M, 2013).

Therefore, The American Petroleum Institute (API) has divided base oils into five categories which comprise the first three groups refined from crude oil, group IV fully synthetic (polyalphaolefin) oil, and group V which consist of all base oil that is not classified in group I to IV. Lubricants primarily start as one or more of these five API groups of base oil before additives and solvent are added.

- Group 1 base oils are made out of less than 90% saturated hydrocarbon extracted from crude oil petroleum. These oils are refined using a solvent extraction process and catalytic hydrogenation. Sulphur contained in these oils is greater than 0.03%. Meanwhile, the viscosity index of this base oil ranges from 80 to 120.
- Group 2 oils are formed through hydrocracking, solvent extraction or catalytic process which comprises more than 90% saturated hydrocarbon, less than 0.03% Sulphur content, and viscosity index still ranging from 80 to 120.
- Group 3 oils are more refined oil compared to group 2 base oil. These oils have greater than 90% saturates, Sulphur content of less than 0.03%, and viscosity index greater than 120. These oils are developed through the hydrocracking process with the rearrangement of the carbon structure.
- Group 4 oils are polyalphaolefins (POAs) with almost 0% of Sulphur content and a viscosity index ranging from 140 to 170. These oils are produced through the synthesizing process of lower molecular weight end terminated olefins. These synthetic base oils are very suitable to be used in cold conditions and high heat applications.
- Group 5 oils are all other base oils such as esters, polyglycols, phosphates esters, bio-lubes, and more. To enhance the properties of the oil, these base oils are frequently mixed with other base fluids. These base oils usually have high thermal stability and high solubility with other substances (Holweger, 2013).

Therefore, the selection of base oil is utterly important for lubricants in two-stroke engines to withstand heat and combustion of fuel without incomplete burning. The base oil is also required to keep the working parts clean from carbon deposits or gummy residues caused by poor combustion. Additives and solvent added to the base oil to improve the properties of the base oil which eventually reduces wear and tear and improves engine efficiency.

2.2.1.2 Bio-Based Oil

About 2.4 billion gallons of lubricating oil per year is needed for the industrial and automotive sectors throughout the world (Erhan, Sharma, & Perez, 2006). Approximately about 95% of the lubricants are petroleum-based which are toxic and non-renewable. These petroleum-based lubricants can be very harmful to the environment during their production, distribution, service usage, or even disposal after their utilization. According to the Brazilian Environmental National Council (CONAMA) states that there are local companies that have registered with them to refine contaminated or used oil and improve environmental management. The improper disposal of petroleum waste is large and cause hazardous to the environment. Therefore, more concern is being raised around the globe for bio-based lubricants due to strict environmental regulation and depletion of world fossil fuel reserves (Luna, Cavalcante, Silva, & Cavalcante, 2015).

Vegetable oil is only comprised of 0.1% of the lubricant market per year. Its biodegradable and non-toxic properties make it an environmentally friendly lubricant. It is becoming a preferred lubricant compared to petroleum based lubricants. Bio-based lubricant is the name given to all lubricants which are made out of living materials such as vegetable or plant oil and animal fats. Bio-based lubricants have valuable and useful physiochemical properties such as good lubricity, high flash point, high viscosity index and good resistance to shear compare to mineral oils. Bio-based lubricants have relatively a high viscosity index which enables it to operate at a wider range of temperatures as per its application requirement. Besides that, these lubricants also have volatility and flash point above the intended operating temperature. In several types of research done before, bio-based lubricants are known good for their lubricity compared to petroleum-based oil, especially on boundary lubrication (Syahir et al., 2017). These lubricants also have long chained FA's which have greater anti-wear and lubricity properties compared to short FA chains. This enables them to maintain low COF values and low wear.

However, bio-based lubricants also have their flaws and disadvantages. Bio-based lubricants have low oxidation stability in their natural form. Besides that, they also have low pour point, high feedstock cost, low evaporation rate, low heating value, and poor cold flow properties when in use in the colder region. Poor low-temperature behavior due to excessive long FA chains is discovered in bio-based lubricants. Due to certain excess poly-unsaturated fatty acids present in these lubricants, oxidation tendency increases. However, the addition of additives and solvent will overcome this negative property. Besides that, transesterification or epoxidation are the solutions to improve oxidation stability at low temperatures (Singh et al., 2017).

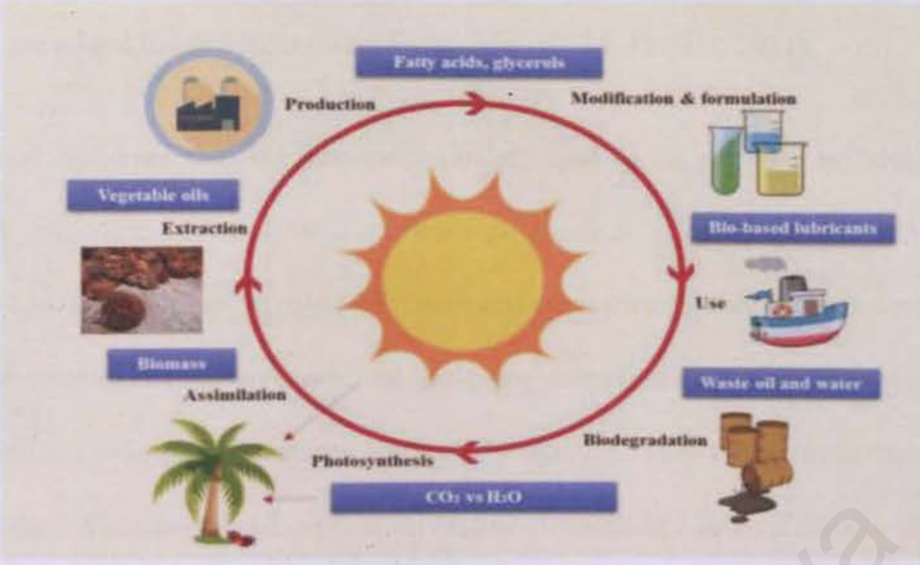


Figure 2.2: The life cycle of bio-based lubrication (Abu Hassan, Mohamad Fauzi, Yeong, & Hassan, 2016)

2.2.2 Additives

From ancient days up to modern days lubrication technology was always been used widely around the world. Most of the machine operations do require lubricating oil to minimize oxidation, avoid rusting, act as insulators, and transmit mechanical power in hydraulic power application. However, the main purpose of lubricating oil is to minimize wear and heat between the surfaces in contact that are relatively in motion. Therefore, lubricants can be considered as the lifeblood of oil wetted machinery in preventing direct contact of rubbing and minimize wear (S & M, 2013).

Additives are important in resolving problems of lubricants. Additives may be any chemical material that is formulated to the base oil to enhance their current properties and impart new characteristics needed by modern engines. Most powerplants, small precision equipment, and road vehicles require additives added lubricant for their hydraulics or engines to run efficiently. Based on the manufacturer's requirement, every additive added to base oil has its specific jobs to perform. Additives are formulated up to almost 20% by their weight to base oil depending on their functionality. Moreover, lubricant performance increases whereby less wear and friction are spotted on moving engine components when additives are added to lubricants (Husnawan, Masjuki, & Mahlia, 2011).

Types of additives that are commonly being used in an engine comprise friction modifiers, anti-wear agents (AW) and extreme pressure additives (EP), anti-oxidant additives (AO), Anti-foam agents (AF), rust and corrosion inhibitors, and detergent or dispersant additives. Friction modifiers are being introduced to minimize friction and wear especially at low temperatures, unlike AW agents. These additives act as a strong low resistance film through adsorption on engine surfaces and lubricating oil. EP agents have a higher activation temperature compared to AW agents. The urgency of additives to avert wear rises when the engine power demand has been increased.

Therefore, the most advanced technology of using zinc dialkyl dithiophosphates (ZDDP) was developed in anti-wear chemistry during the 1930s and 1940s. These compounds exhibit unusual anti-wear and antioxidant characteristics besides preventing corrosion on bearing in the engines. AV and EP additives are activated by heat decomposition that reacts with metal surfaces and forms a thin layer that shears under boundary lubrication conditions. When EP additives chemically react with metal surfaces a strong protective film is formed. Besides resisting high temperature and mechanical pressure, this protective film also prevents surfaces from having direct contact (S & M, 2011)

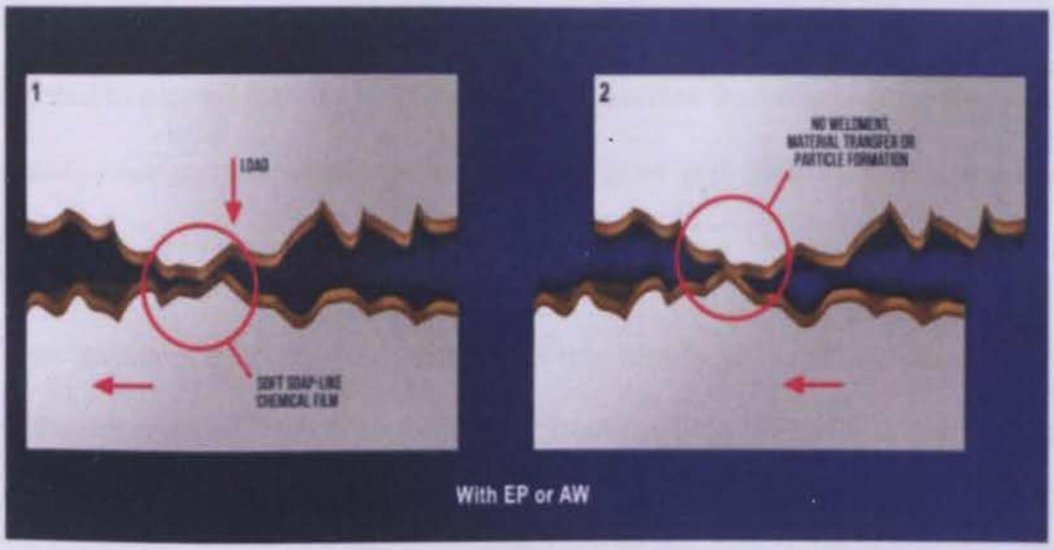


Figure 2.3: The reaction of anti-wear agent additives (solution, 2019)

The maximization of oxygen stability is a major aspect of lubricating oil's properties. The oxidation process will speed up even greater when hydrocarbons are exposed to oxygen and heat. Therefore, the addition of antioxidant additive is important to prevent oxidation of hydrocarbon into solid materials such as fatty acids, fatty alcohol, ketone, and fatty peroxides at high temperatures. The oil stability has to be enhanced against oxidation due to its high ability of oxidizing at higher temperatures, higher pressure, and friction in the engine. For the lubricants to achieve the required demands for the use in engine and other applications, antioxidants additives play a major role in preventing the lubricants from having oxidative degradation (S & M, 2011).

Lubricants cannot be considered as fully free from air contamination because it continuously undergoes exchange process with its air-containing environment when being stored in containers or operation within the engine. Foams that present in the lubricant is considered as undesirable because it impedes with the lubrication process and causes an error in the level of the lubricant. It also causes extreme wear due to the existence of compressible air bubbles. Moreover, foaming in lubricants also increases the oxidation process when it mixes up with air. It also causes inadequate supply in the circulation system which leads to a lack of lubrication. Therefore, anti-foam agents were developed to prevent foaming by eliminating the bubbles from reaching the free surface. Materials such as polymethyl siloxanes inhibit great anti-foaming ability and widely being used in engine oils (M.Abd-Elfattah, 2018).

Rust inhibitors are compounds that form a thin film by physical or chemical reaction with the metal surface which impedes water from reaching the metal surface. Materials such as amine succinates and alkaline earth sulfonates are mostly used as a rust inhibitor compounds. Selecting suitable rust inhibitors for lubricants is important to prevent problems like corrosion of non-ferrous metal or formation of troublesome emulsion with water. Few types of corrosion can happen with the presence of water in a lubricating system. Firstly, corrosion is caused by organic acids that develop within the oil itself. Secondly, corrosion is caused by contaminants that are collected and carried by the oil. Therefore, corrosion inhibitors are needed as a protective layer on the bearing surfaces to eliminate corrosive substances that attack the metal surfaces. The addition of high alkaline material to the lubricants will enhance the neutralization of strong acid formed and reduce corrosion or corrosive wear (S & M, 2011).

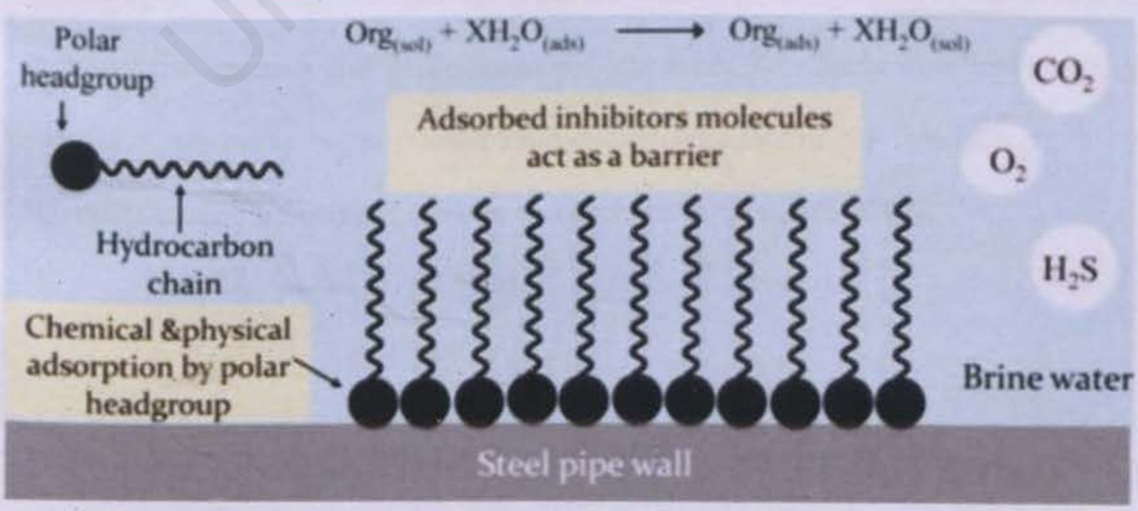


Figure 2.4: Schematic action of corrosion inhibitors (Ibrahim, 2011)

There are many deposits from the various sources are found in the engines. These deposits are mainly from the used fuel and lubricant, poor combustion quality, lubricating oil, and coolant temperatures, and the gas sealing off the ring in the cylinder. Engines will have a shorter life if these accumulated deposits in the engine are not drained off together with oil when the oil change maintenance takes place. Automotive lubricant faces challenges in suspending undesirable products from thermal and oxidation degradation of the lubricant itself. Lubricant oxidation is initiated by the after products of fuel combustion like hydroperoxides and free radicals that react with the lubricant itself. Later the oxidation products form surface deposits and clog small openings. Therefore, detergents and dispersants are developed to control deposit formation by preventing oxidation degradation and suspending the harmful product formed in the bulk lubricant. Detergents are metal salts of organic acids while dispersants are metal-free and are off higher molecular weight than detergents. Both works in combination to neutralize the acids and suspend non-acidic oxygenated products that form in the engine.

2.2.3 Solvent

The solvent is mixed with lubricants to enhance the lubricant properties. The higher the solvent to oil ratio the greater its ability to remove sludge from the oil besides increasing the percentage of recovering the oil. Moreover, the addition of the solvent also improves the viscosity and flashpoint of the lubricants. To achieve excellent miscibility with fuel, two-stroke engine oils are traditionally comprised of ~65-75% base oil, ~5-30% solvent (Oladimeji, Sonibare, Omoleye, Adegbola, & Okagbue, 2018).

2.3 Two-Stroke Engine Oil

The global demand for two-stroke engine oil has raised approximately 10 million gallons per year compared to four-stroke engine oil which is only 4 million gallons per year as recorded in year the 2013 (Insight, 2013). Approximately, about 9200 units of two-stroke engines were brought in to Malaysia in the year 2016 for numerous applications such as the vehicle industry, marine application, smaller machinery, and more. Due to the low lubricity of fuel, a two-stroke engine requires a two-stroke engine oil to reduce friction and wear during operation. Presently the manufacturing of two-stroke engine oil is governed by petroleum-based base oil as it is manufactured on a large scale by petroleum producers.

Since the demand rises for two-stroke engine oil, the price of petroleum-based two-stroke engine oil becomes significantly expensive. However, the burning of premixed two-stroke lubricants and fuel together in the combustion space emits more smoke, carbon monoxide, particulate matter, and hydrocarbon to the environment. This is due to the lubricating oil is mixed with fuel and burned together in combustion space while the gases are exchanged via ports located at the cylinder. The exhaust contains a high level of unburned fuel and lubricant which ease further environmental pollution (Begum et al., 2006). Thus, the application of two-stroke engine oil in the marine engine for fisherman activity has raised concern on environmental issues like air pollution and leaking of toxic engine oil which harm water bodies of sea, lake, and river.

Therefore, the use of bio-based feedstock such as PFAD-NPG ester as a base oil in two-stroke engine oil has to be reviewed and studied to enable fishermen to operate their boat fitted with two-stroke engines without any restriction from authority's due environmental pollution.

2.4 Two-Stroke Engine Performance Testing

In the year 2019, (Zulfattah et al., 2019) have investigated the effects of bio-based lubricants towards emission and engine break down due to spark plug fouling in a two-stroke engine. In his research, he has used Trimethylolpropane Trioleate (TMPTO) ester derived from palm oil using two esterification processes as bio lubricant in comparison to commercial mineral base two-stroke engine oil. The different blend ratios of mineral base oil (TO) and TMPTO were prepared into four samples and compared with pure TO. Then the best blend ratio of TO: TMPTO was analyzed for a good combustion quality and exhaust emission in a two-stroke engine. A two-stroke brush cutter engine was used to run at idling speed till the premix fuel gasoline is completely burn off. The carbon deposits on the NGK BM6A plug were analyzed. For the exhaust emission, the Bosch BEA 350 Emission analyzer and Test Smoke Opacity meter were used. The smoke opacity meter was fixed at the tailpipe of the brush cutter to record the carbon monoxide CO, carbon dioxide CO_2 and hydrocarbon HC emission. Through his research, he has concluded that the addition of bio-based lubricant in optimal ratio to base oil has led to the complete combustion of premix fuel to occur without any carbon deposits at electrodes. TMPTO added samples have shown a better viscosity compared to pure TO tested.

CHAPTER 3: METHODOLOGY

3.1 Introduction

To improve and study the enhancement for two-stroke engine oil, many types of research have been carried out. The samples were prepared by mixing three components of oil which comprised base oil, additives, and solvent. In this research, the base oil used were PFAD-NPG ester and Group II mineral, additives package which comprised GO (graphene oxide), Anti-oxidant (AO), PIB1300, PIB1100, ZDDP, and a solvent D80N. Lubricant additives mixing ratio were made by the previous researcher in University Malaya and blended into base oil used to prevent corrosion, reduce smoke, control oxidation, and reduce friction. The D80N solvent was used to lower the flashpoint of the lubricant. Firstly, the mixture of oil was investigated on the physicochemical properties such as density, viscosity index, kinematic viscosity, and dynamic viscosity. The parameters measured were the viscosity values of each sample. Next, the friction and wear performance of the oil mixture were determined by using a four-ball Tribotester. An optical microscope was used to analyze the worn surface of the ball bearings used in the four-ball experiment. The effect of the lubricant mix on the piston ring cylinder linear interaction was concluded based on the WSD on the ball bearings. The parameters measured were COF values and WSD values for each sample. An engine performance test with spark plug ignition was carried out to determine the presence of carbon deposits. Spark plug analysis was conducted once the engine run was completed. The parameter measured was the engine performance test duration for each sample to undergo complete combustion with fuel without abrupt stop. Finally, the experimental data were compared with EVINRUDE Johnson reference oil used in this research.

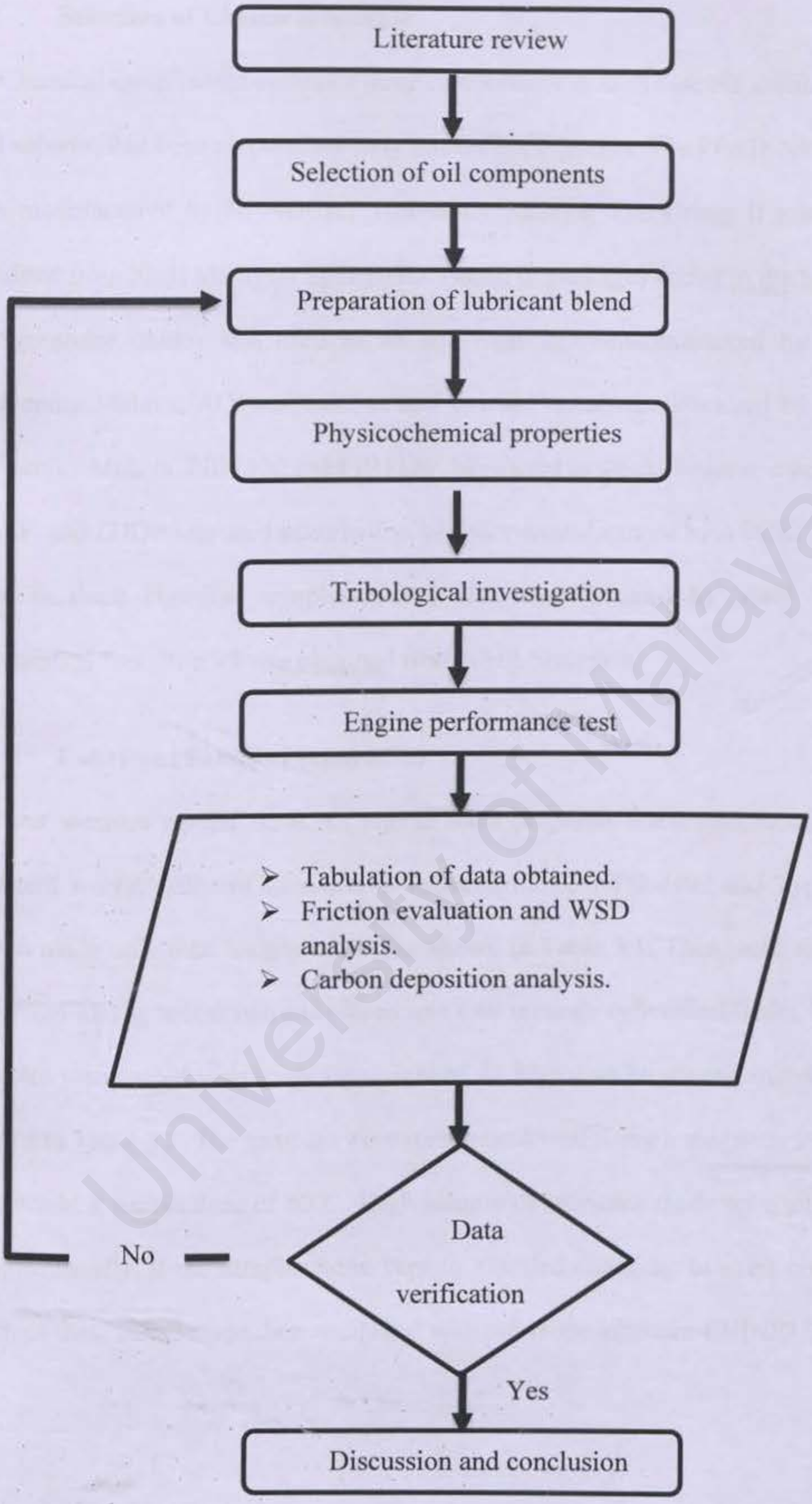


Figure 3.1: Research methodology flow chart

3.2 Selection of Chemical Sample

Chemical samples that comprise three components such as base oil, additive packages, and solvent, that been prepared to carry out the experiments. The PFAD-NPG ester used, was manufactured by NANOCAT University Malaya. The Group II mineral oil was obtained from Shell Malaysia SDN BHD. Additive packages added to the base oils were GO(graphene oxide) was used as an anti-wear agent-manufactured by NANOCAT University Malaya, AO was used as anti-oxidant agent-manufactured by NANOCAT University Malaya, PIB1300 and PIB1100 were used as smoke reducer-manufactured by BASF, and ZDDP was used as corrosion inhibitor-manufactured by ADEKA. The solvent used in these chemical samples was D80N, manufactured by Shell Sol. For the combustion fuel, Ron 95 was obtained from Shell Malaysia.

3.3 Lubricant Sample Preparation

Four samples named A, B, C, and D were prepared. Each sample comprises two different weight ratios of base oils in between PFAD-NPG ester and Type II mineral which made up a total weight of 15g as shown in Table 3.1. Then, each sample with a weight of 11.18g was drawn and placed into four separate cylindrical flasks. Later all four samples were added with a similar weight of 28.82g of additives and solvent mixture as shown in Table 3.2. The samples were then mixed well using a magnetic stirrer for five minutes at a temperature of 60°C. Each sample of lubricant made up a total of 40g by weight. Finally, these samples were kept in a sealed container to avert contamination. Each of these sample was then compared with reference lubricant EVINRUDE.

Table 3.1: Base oil blend preparation

Samples	Base Oil Which Comprises of				Total (g)
	PFAD-NPG		Group II		
	wt.%	g	wt.%	g	
A	30	4.5	70	10.5	15
B	40	6	60	9	15
C	50	7.5	50	7.5	15
D	60	9	40	6	15

Table 3.2: Additives, solvent, and base oil content in each sample

Additives	**wt.%**	**g**
GO (graphene oxide)	0.05	0.02
AO	1	0.4
PIB1300	20	8
PIB1100	20	8
ZDDP	1	0.4
Solvent		
D80N	30	12
Total Additives and Solvent in Each Sample	72.05	28.82
Base Oil in Each Sample	27.95	11.18
Grand Total	**100**	**40**

3.4 Measurement of Physicochemical Properties

Kinematic viscosity, dynamic viscosity, viscosity index, and density were the physicochemical properties that have been investigated and determined for each sample of lubricant prepared. The purpose of this physicochemical properties' analysis was to indicate the quality of lubricant formulated for two-stroke engine applications. The table below shows the list of methods and equipment used to carry out the physicochemical properties' experiments. The equipment used these experiments were calibrated and some of the experiment was repeated to observe any errors that need to be analyzed.

Table 3.3: List of methods and equipment's used for testing lubricant properties

Property	Equipment	Standard Method	Accuracy
Kinematic and Dynamic Viscosity	SVM 300 STABINGER VISCOMETER	ASTM D2270	±0.35%
Viscosity Index	SVM 300 STABINGER VISCOMETER	ASTM D2270	±0.01%
Density	SVM 300 STABINGER VISCOMETER	ASTM D2270	0.0001 g/cm3

3.4.1 Kinematic Viscosity, Dynamic Viscosity, and Viscosity Index

Viscosity is one of the major physicochemical properties in lubricating oil. It determines the internal friction within the liquid due to molecular interaction and also impacts the ability of the oil to form a lubricating film during operation (Syahir et al., 2017). Dynamic viscosity or absolute viscosity is a measure of the degree of stickiness that resists the direction of a substance's motion in the state of flowing fluid. Kinematic viscosity is a relative indicator of a fluid's internal resistance to flow under gravitational forces. Kinematic viscosity can also be considered as the ratio of dynamic viscosity to the density of fluid where no forces are required. Viscosity index is a dimensional number that measures the viscosity behavior of lubricants based on temperature. Viscosity index is vital to enable suitable lubricants to be used on engines or machinery when temperature changes occur during operation. Anton Paar's Stabinger Viscometer ™ SVM ™ 3000 was the viscometer used in this research to measure kinematic and dynamic viscosity and viscosity index. It determined the physicochemical properties of the samples prepared at 40°C and 100°C of temperature as per the ASTM D2270 standard method. The experiment was carried out at Tribology Lab, Faculty of Engineering, University of Malaya in Kuala Lumpur.

Figure 3.2: SVM3000 STABINGER viscometer

3.4.2 Density

Density is one of the important properties that need to be considered not only in engine lubricants but in all types of fluids. Density is a measure of the mass of a substance to a known volume. However, the density of lubricants varies with the temperature. For instance, when the temperature increases in a lubricating oil, the oil will expand and causes a decrease in its density. As the density of lubricant rises, the fluid becomes thicker and will affect the dynamic viscosity. Therefore, the density of lubricants in vital in selecting a suitable engine lubrication oil. Anton Paar's Stabinger Viscometer ™ SVM ™ 3000 was used in this research to identify the density of samples prepared based on the ASTM D4250 standard. The experiment was carried out at Tribology Lab, Faculty of Engineering, University Malaya in Kuala Lumpur, Malaysia.

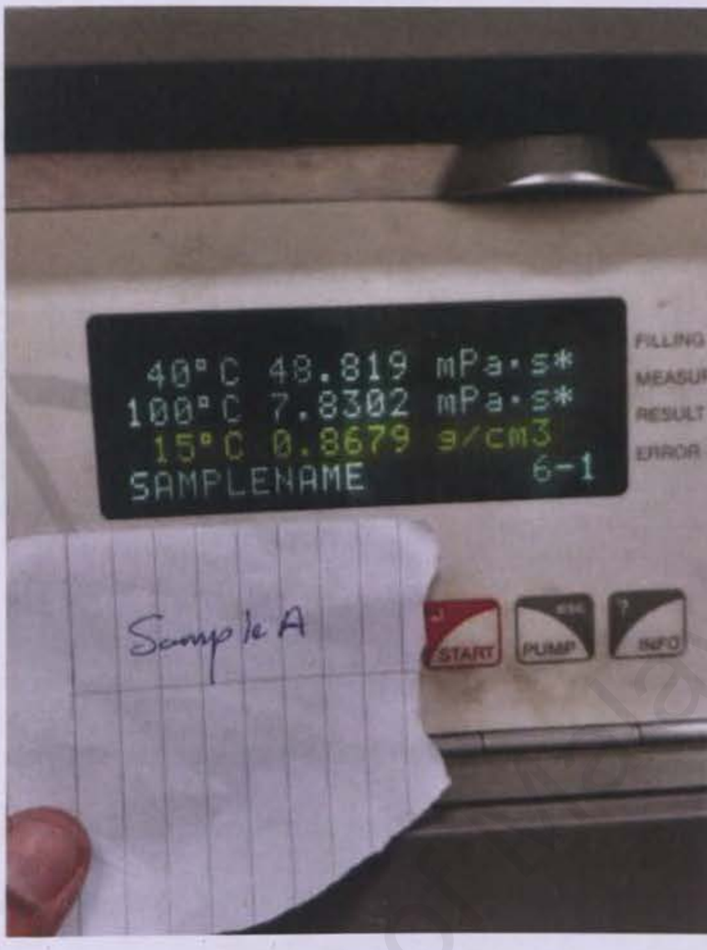
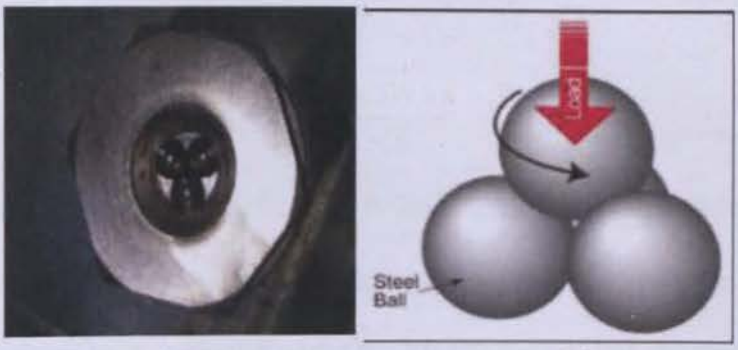


Figure 3.3: Density measurement taken with SVM3000 STABINGER viscometer

3.5 Tribological Investigation

Wear reduces the life of material and causes failures on mechanical parts whereas friction causes loss of energy and reduces the overall efficiency of the mechanical components (Marko, Kyle, Wang, & Terrell, 2017). In this research, a calibrated four-ball tribo-tester assembled by DUCOM TR-30H was used to determine the tribological properties of samples prepared in comparison with reference lubricant, according to the standard test method of ASTM D2783. These experiments were carried out at Tribology Lab, Faculty of Engineering, University of Malaya in Kuala Lumpur, Malaysia.

This machine consists of the device in which a ball bearing can be rotated in contact with three fixed ball bearing which was immersed in the sample prepared. The upper rotating ball was connected to the rotating shaft via a chuck. The three fixed ball bearings below were assembled in a ball pot by clamping ring and lock nut and tightened using a torque wrench (Habibullah et al., 2014). The arrangement is shown in figure 3.4.



(a) (b)

Figure 3.4: Arrangement of four-ball (a) three lower ball bearings in ball pot (b) complete arrangement of the four-ball bearings (W, 2015)

The ball bearings used in this experiment were made of EN31 steel with a diameter of 12.7mm and a surface finish of 0.1μm CLA. Each ball bearing and ball pot was rinsed with acetone and wiped clean to remove any residual before each sample was tested. For each test being carried out, a sample volume of 10 ml was required to cover the ball's depth of at least 3mm. The test conditions were fixed at a constant temperature of 75°C, a rotational speed of 1200 rpm, a constant load of 40kg, and an operation period of 3600s for all samples and reference lubricant.

Figure 3.5: Four-ball-tribotester

3.5.1 Friction Evaluation and Wear Analysis

The coefficient of friction was calculated according to IP-239 by multiplying the mean friction torque and spring constant. The friction torque on lower balls can be derived as:

$$T = \frac{\mu \times 3W \times r}{\sqrt{6}} \qquad [1]$$

where T = the frictional torque (kg mm), W is load in kg and r is the distance from the contact surface of the lower ball to the axis rotation. The coefficient of friction was automatically tabulated by a computer with DUCOM software. For the wear analysis, the wear produced by the three lower ball bearings was analyzed using a calibrated optical microscope and the SCARVIEW software was used to measure the wear scar diameter (WSD) as shown in figure 3.6 (W, 2015). The observation was carried out at Tribology Lab, Faculty of Engineering, University of Malaya in Kuala Lumpur, Malaysia. The analysis was repeated to observe any error need to be analyzed.

Figure 3.6: Optical microscope used to analyze the lower three ball bearings.

3.6 Carbon Deposition Analysis

The engine performance testing was carried out by using a 43cc brush cutter two-stroke engine. Heat Engine Lab, Faculty of Engineering, University of Malaya in Kuala Lumpur, Malaysia was used to run this engine performance testing for all the sample and reference lubricant prepared. The recorded ambient lab temperature was 32°C with a moisture level of 70%. Ambient air pressure was 1010mmHg. Fuel to lubricant ratio for reference lubricant EVINRUDE Johnson was kept at 50:1 as recommended by the lubricant manufacturer. For the four samples prepared, the ratio was kept at 40:1 as recommended by a previous researcher from University Malaya. Ron 95 unleaded fuel from Shell Sdn Bhd was used as fuel supply in this research. A total of five engine performance tests with new spark plugs were carried out for four sample lubricants and a reference lubricant. The engine specification and other related parameters are listed in table 3.4.

Table 3.4: Engine specification

Specification	Parameter
Type of engine	1E40F-5C, two-stroke, air-cooled, vertical piston
Bore diameter (mm)	40
Displacement (cc)	42.7
Idling speed (rpm)	2500 ± 150
Carburetor	Float type
Maximum output (kw/rpm)	1.25/6000
Spark Plug	NGK BM6A, 14 Ø x 9.5 mm, short thread, nickel electrodes
Fuel	Unleaded gasoline Ron 95

In this engine performance test, carbon deposition on the spark plug was analyzed. At idling speed, 1 liter of premixed fuel and lubricant was used to run the engine without any load. The engine ran at the slowest rpm with no added load when it is idling. This ensures there was no external stress on the running engine. A good lubricant blend ensured complete combustion has taken place around this temperature and clean operation throughout the engine operating range (Zulfattah et al., 2019). A new spark plug was used for each engine performance test carried out to determine the carbon deposits on the plug.

Figure 3.7: Engine testbed

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Physicochemical Properties

4.1.1 Kinematic Viscosity, Dynamic Viscosity, and Viscosity Index

The most important aspect of a lubricant is viscosity as it affects the film thickness and wear rate of sliding surfaces.

Table 4.1: Properties of sample lubricants and reference lubricant

Samples	PFAD-NPG (wt.%)	Properties				
		Kinematic Viscosity (mm^2/s)		Dynamic Viscosity (mpa/s)		Viscosity Index
		40°C	100°C	40°C	100°C	
Reference Lubricant	0	72.197	10.399	61.705	8.4932	129.5
A	30	57.266	9.6018	48.819	7.8302	152
B	40	58.941	9.9064	50.356	8.0974	154.4
C	50	57.41	9.6513	49.106	7.8675	152.8
D	60	55.216	9.5441	47.29	7.8512	157.6

Table 4.1 shows the effect of kinematic viscosity and dynamic viscosity of the samples and reference lubricant at the temperature of 40°C and 100°C respectively. From the table, it shows that sample B has the highest value of kinematic viscosity at 40°C which is 58.941 mm^2/s comparatively to other samples tested. However, the reference lubricant has recorded the highest kinematic viscosity which 72.197 mm^2/s. Based on the table; it also can be seen sample B that the highest kinematic viscosity at 100°C compared to other samples as well. The kinematic viscosity of all samples is lower at 100°C compared to 40°C. At a higher temperature, the kinematic viscosity was lower due to the liquidity of the sample lubricant. It can be said that sample B has the best PFAD-NPG ester to Group II mineral weight ratio to maintain the anti-wear aspects like kinematic viscosity.

As for the dynamic viscosity, sample B also exhibits the highest viscosity which is 50.356 mpa/s but lower compared to the reference lubricant which is 61.705 mpa/s at 40°C. The dynamic viscosity of lubricant has to be high so that the lubricant able to form a thicker protective layer at higher temperatures. The influence of a temperature change in the viscosity of lubricant oil is termed as Viscosity Index (VI) number. At high temperatures, the oil becomes exceptionally thin whereas at low temperatures it becomes exceptionally thick. A lubricant with a high VI number only has a slight effect on its viscosity over a broad temperature span. The ability to maintain a constant viscosity throughout varying temperature is ideal for a good lubricant. When the engine is cold, a high VI lubricant prevents excessive thickening while enhancing rapid starting and prompt circulation. Meanwhile, when the engine is hot, the high VI oil prevents excessive thinning and provide full lubrication while reducing excessive oil consumption (Zulkifli, Kalam, Masjuki, Shahabuddin, & Yunus, 2013). From table 4.1, shows that the VI of sample D is the highest which is at 157.6 compared to reference lubricant oil which is 129.5. However, considering other physicochemical properties data and a VI of 154.4, sample B will be the best option of all the sample lubricants tested relative to reference lubricant.

4.1.2 Density

The density of oil enables it to determine its composition and nature. The density of lubricants, mostly hydrocarbon, ranges between 0.860 g/cm³ to 0.980 g/cm³.

Table 4.2: Density of reference lubricant and samples

Samples	RL	A	B	C	D
Density (g/cm³)	0.8705	0.8679	0.8697	0.8721	0.8721

Based on table 4.2 the density of the samples and the reference lubricant is almost similar and there are no significant changes due to different base oil weight ratios.

4.2 Friction Evaluation

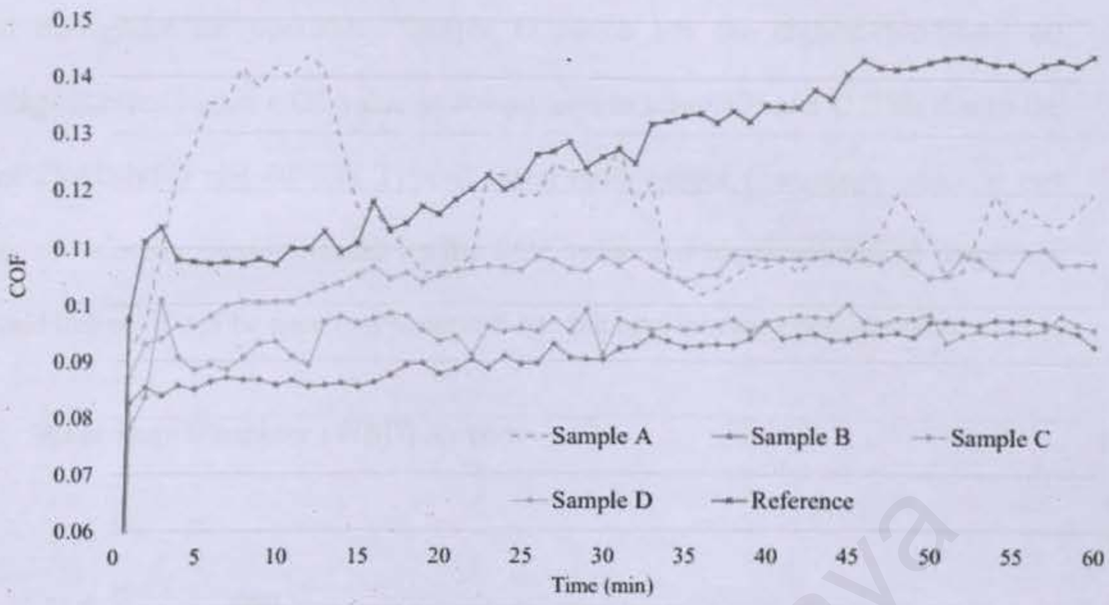


Figure 4.1: Coefficient of friction for samples and reference lubricant

Table 4.3: Bio-based feedstocks percentage present in each sample

Samples	Base Oil Which Comprises of	
	PFAD-NPG (wt.%)	Group II (wt.%)
A	30	70
B	40	60
C	50	50
D	60	40

The values of COF (coefficient of friction) for the different lubricant samples and reference lubricant are shown in figure 4.1. All the samples show a lower coefficient value compared to the reference lubricant due to their bio-based base oil formulation. Reference lubricant exhibits the highest value of COF, most likely due to mineral-based oil being used in their formulation. This agrees with the research showing that the different weight percentage of PFAD-NPG to Type II base oil that presents in all four samples tends to develop a thin film that acts as a separator from asperities and produce a lower COF value. Sample A showed a heavy fluctuation in its COF value indicating an unstable tribo-layer.

Sample B and C showed similar trends and COF values indicating stable tribo-layer being formed throughout the operation. Sample D which has the highest bio-based oil percentage showed higher COF value in comparison to sample B and C. This due to the 60% of PFAD-NPG and 40% of Type II blend ratio weight percentage which is not capable of reducing friction. Based on the COF value and physicochemical properties discussed before, it can be seen that sample B has the best lubricity performance.

4.3 Wear Scar Diameter (WSD) Analysis

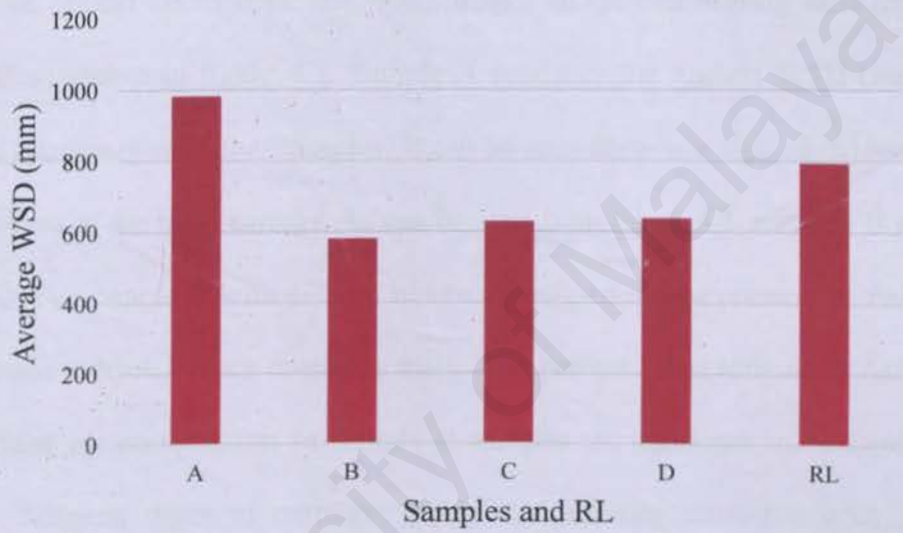
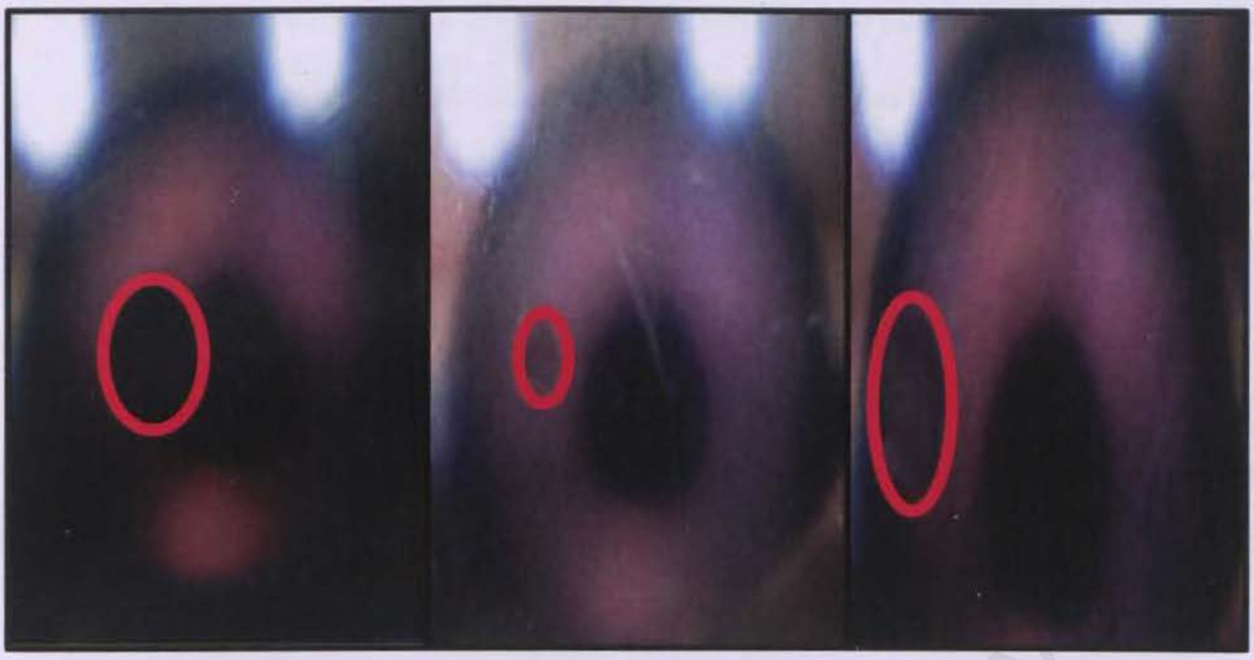


Figure 4.2: Wear scar diameter of samples and reference lubricant

Figure 4.2 shows the variation in average wear scar diameter (WSD) for different samples and reference lubricant at a constant load of 40kg. The average WSD is related to damage that occurred due to the removal of material from three sliding contact and a solid surface. Based on the results in figure 4.2, it can be seen that the WSD for sample B was the lowest which is 580.69mm compared to the reference lubricant which is 794.35mm. This data shows that sample B possess a good anti-wear behavior due to its high viscosity value compared to other samples and reference lubricant. The wear scar is reduced when the high viscous oil forms a thick lubricating film between the contacting surface. The long fatty acid chains of PFAD-NPG bio-based oil in sample B increase the adsorbed film thickness which provides greater resistance to shear forces while increasing the surface area protected (Zulkifli et al., 2013). Sample A exhibits the highest WSD which 983.5mm due to its blend ratio that is not capable of forming a strong lubricant film between contacting surfaces, thus fail to reduce wear. Both samples C and D show almost similar WSD values which are 628.91mm and 637.68mm respectively. This result has shown that both samples C and D able to reduce wear compare to sample A and reference lubricant thorough out the operation.

Using an optical microscope, the WSD images on the ball bearing were observed at 40kg load as shown in figure 4.3. Sample A produces the highest WSD compared to reference lubricants and other samples. It can be seen there is a sign of oxidation stains on the surface of the ball bearings. As can be seen from figure 4.3, samples B shows the best WSD. For sample B with 40% of bio-based oil percentage present, its ball-bearing surface tends to have a black corrosive mark. The perfect blend ratio of PFAD- NPG to Type II base oil composition in sample B enables the lubricant to be oxidized and produces different types of corrosive acids that enhance corrosive wear at higher temperatures. Therefore, the presence of PFAD-NPG oil in base oil composition enables samples B, C, and D to improve oxidative stability by forming a thicker protective layer on the surface of ball bearing which is less susceptible to oxidative attacks.



(A) (B) (RL)

Figure 4.3: Wear scar image for the optical microscope of sample A, B, and RL

4.4 Carbon Deposition Analysis

In every engine performance test, the engine throttle was kept at idle till the entire fuel filled up is completely burned and the engine comes to a stop whereby spark plug fouling or carbon fouling happens. The carbon deposition in a spark plug usually takes place at areas disclose to combustion such as the insulator tip, side electrode, the center electrode, and electrode circumference.

Table 4.4: Engine operation time for each sample

Samples	Period of combustion/ Engine operation time
A	3 hours and 1 minute
B	3 hours
C	2 hours and 59 minutes
D	2 hours and 57 minutes
RL	3hours and 15 minutes

Based on table 4.3, the period of combustion taken by each sample is almost similar but differ by approximately 15 minutes to 18 minutes earlier than the reference lubricant. Reference lubricant took the longest engine operation time which is 3hours and 15minutes while sample D recorded the fastest operation time of 2 hours and 57 minutes. Throughout the operation and test, no samples or references lubricant were recorded to have an engine abrupt stop without burning off the premix fuel completely. This proofs that the engine is running efficiently regardless of vibration produced throughout the operation. All samples including the reference lubricant were seen to have carbon deposits. To determine the adequate combustion quality of lubricant samples, idling engine speed was chosen for rapid and simple visibility of carbon deposition. A char built up at the spark plug circumference when premix fuel loses part of its hydrogen and oxygen bonds due to high pressure and temperature caused by the combustion cycle. Nevertheless, spark plug electrodes faced the highest temperature inside the combustion chamber. Eventually, this char started to cover up the ring surface of the plug and develops their deposits from the circumference of the plug up to the center and sides of the electrode.

Based on engine performance tests carried out by (Zulfattah et al., 2019) using TMPTO as a bio-based lubricant, he found that all the duration of combustion for all samples with different ratios of bio-based feedstock is similar but not identical. The longest operation recorded based on his research was TO and T15 samples which were 7hours and 5 minutes. The rest of the samples were less by 1 minute except for T50 which had the highest ratio of bio-based lubricant had stopped at 3hours and 34minutes without burning the fuel completely. Through his research, he found carbon deposits for all the lends. Generally, he found the least deposits in his sample T15 with a 15% ratio of TMPTO followed by T20, T0, T10, and T50. Sample T15 and T20 had carbon deposition on the spark plug circumference whereas both electrodes and insulator tips were free from carbon deposits. This shows T15 and T20 have undergone complete combustion and suffers normal burning. Therefore, he had concluded that optimal ratio-to-mineral mixture leads T15 and T20 to burn completely during combustion which leaves both electrodes free from carbon deposits.

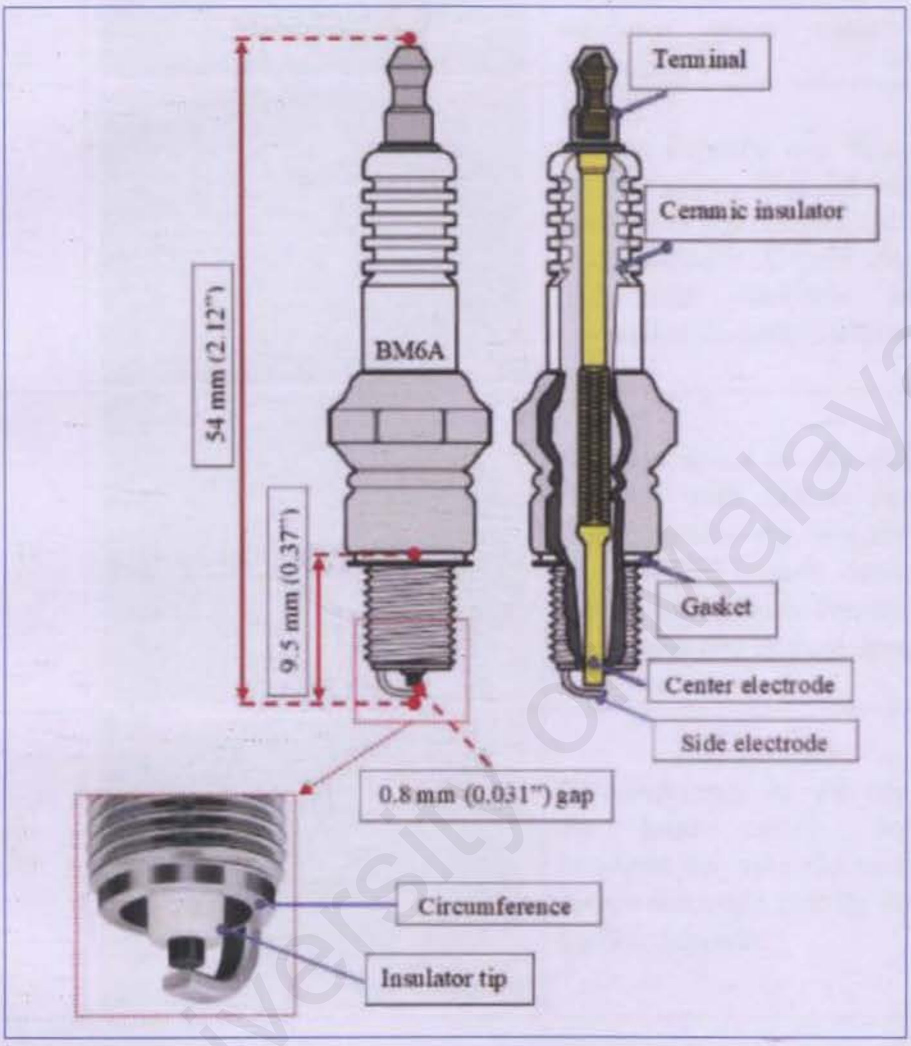


Figure 4.4: Simple configuration of the spark plug used (Zulfattah et al., 2019)

Table 4.5: Carbon deposits on spark plug with different sample blends.

Sample	Plug Condition	Description of carbon deposits	Ranking
A		All four areas of the plug are covered with carbon deposits. Dry deposits can be observed at the side electrode, center electrode, and the tip of the electrode. At the circumference of the plug, wet deposits can be noticed.	4

B		Carbon deposits can be considered very minimal. Circumference was covered with wet deposits. Side electrodes were noticed to be coated with slight dry deposits. The Center electrode and the tip of the insulator were clear from deposits.	1
C		Carbon deposits can be seen in all four areas. Wet deposits and greasiness can be noticed at the circumference. Center electrode and side electrode heavily covered with carbon deposits.	3
D		All four areas of the plug are covered with carbon deposits. The insulator tip is noticed to have partial carbon deposition. The plug circumference has greasiness and carbon deposits.	4
RL		Circumference of the plug has the least carbon deposits. Insulator tip, side electrode, and center electrode heavily covered carbon deposits.	5

As can be seen from table 4.4, the circumference of the plug was covered with a wet deposit for sample B. The side electrode has been noticed to have slight carbon deposits whereas the tip of the insulator and the center of the electrode is clear from deposits. This can be said that the electrodes and insulator tip have undergone normal combustion and no deposits were formed due to higher combustion temperature. It can be seen that sample B had similar carbon deposition as sample T15 and T20 researched by (Zulfattah et al., 2019). Therefore, a greater cleaning rate was obtained for sample B compared to sample A, C, D, and reference lubricant.

CHAPTER 5: CONCLUSION

5.1 Conclusion

Based on the experimental results obtained we can conclude that the use of PFAD-NPG ester of different weight ratios to Type II mineral as a base oil has significantly affected the physicochemical properties and tribological behaviors samples prepared in comparison to reference lubricant. By mixing different weight percentages of PFAD-NPG ester in the samples, the kinematic and dynamic viscosity has increased and formed a thick lubrication film that improves friction and wear properties of the lubricant. Sample B has shown the highest viscosity index comparatively to other sample and reference lubricant.

Besides that, the tribological investigation which comprises COF evaluation and WSD analysis also prove that the addition of bio-based lubricants has remarkably reduced the COF value and WSD compared to commercial lubricants. Based on the optical microscope view result, Sample A has the highest WSD compared to other samples and reference lubrication. Sample A was mixed with the lowest weight percentage of bio-lubricant which have poor wear prevention. Thus, an optimal weight ratio of 40% PFAD-NPG ester to 60% Type II mineral base oil that presents in Sample B exhibits the best physicochemical and tribological properties in these experiments carried out.

In terms of carbon deposit analysis, Sample B has undergone complete combustion without leaving behind any deposits in its electrodes and insulator tip compared to other samples. However, the RL shows minimal deposits at circumference but heavy deposits at both electrode and insulator tip which indicates the initial sign of carbon fouling. In conclusion, the use of PFAD-NPG ester or any other bio-based lubricant should be encouraged to substitute mineral and synthetic based lubricants for a cleaner environment and greater energy saving in two-stroke marine engine application.

5.2 Recommendations

Through this research, it can be justified than bio-based lubricants have shown extraordinary lubricant properties compared to commercial petroleum-based lubricants. As the nation concern about depletion of petroleum-based products, the bio-based lubricant is expected to have more demand soon due to their environmentally friendly and nontoxic emissions. Moreover, the development of non-edible vegetable oil enhances the continuous supply of raw material for manufacturing bio-based lubricants in the near future.

However, a major setback comes in when the cost production of bio-based lubricants is considered to be high by local manufacturers and commercial users. Therefore, upcoming research should focus more on large scale bio-lubricants manufacturing efficiency with a minimal cost of production. Thus, petroleum-based lubricants can be neglected completely for a better energy-saving and the environment in marines and forestry. The use of bio-based oil in marine engine applications is vital due to stringent law by local authorities on not polluting the sea life environment. Therefore, the manufacturing of bio-lubricants at lower cost will help these small engine users to sustain their life.

Besides that, more studies of evaluating other properties like oxidative, thermal, and hydrolytic on bio-based lubricants need to be done to achieve a great quality of engine oil which can permanently replace petroleum base oils. Researchers, lubricant manufactures, standard organizations have to work together for the continuous development of bio-based lubricants in terms of performance guidelines and testing procedures.

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