Journal of Mechanical Engineering *Vol SI 5(2), 142-156, 2018*

The Effect of Low Temperature Test on Lubrication Performance of Palm Kernel Oil with Addition of PPD as A Lubricant (ASTM D4172)

*Aiman. Y**
Syahrullail. S

FACULTY OF MECHANICAL ENGINEERING, UNIVERSITI TEKNOLOGI MALAYSIA, 81310 UTM SKUDAI, JOHOR, MALAYSIA.

**Corresponding author: wmaiman91@gmail.com*

ABSTRACT

This paper present a case studies to highlights the importance of renewable and sustainable material to develop a bio lubricant. A research has been done to study the low temperature performance and to investigate the low temperature tribological performance of the palm kernel oil with addition of different percentage PPD (5w%, 10wt%, 20wt% and 30wt %) according ASTM D4172. The main analysis that been done in this research are low temperature performance ability of blended PKO, coefficient of friction (COF), wear scar diameter (WSD), surface roughness and surface profile. The result of the experiment show that for low temperature performance, PKO with 20wt%PPD (A2-20%) and 30wt%PPD (A2-30%) show great performance which can withstand lower temperature (15 ℃). Under low temperature test tribological performance the coefficient of friction (COF) is increase as the starting temperature is lower with A2-30% has the highest COF. For wear scar diameter it can see that palm kernel oil having high wear scar compare to A2-5%, A2-10%, A2-20% and A2-30%, the trend shows that adding PPD successful improve the lubricity performance in terms of wear scar diameter. The low starting temperature slightly has effect the lubricity performance in terms of surface roughness. At 75˚C the surface roughness is decreasing from A2-5% to A2-20%. Abrasive wear was the dominant wear mechanism for all sample at all starting temperature and a few adhesive wear were spotted at all test.

Keywords: *Palm kernel oil; PPD; low temperature test; ASTM D4172*

ISSN 1823- 5514, eISSN 2550-164X
Received for review: 2017-04-10
Accepted for publication: 2017-05-22
Published: 2018-01-31

1 Introduction

Lubricant is very important in tribological performance in reducing the wear and friction. For better understanding the characteristic effect wear and friction between two moving surfaces, the researchers need to investigate and study the reaction and the fluid present between the moving surfaces. Under boundary lubrication conditions, a sufficient protective lubricant film on the rubbing surfaces plays a main role in the construction of lubricant film layer and controlling the wear behaviour of the test system [12][28]. According to Castro et al., (2005) load can affect the tribological characteristic of the lubricant. Nowadays many researcher is trying to develop new lubricant especially biolubricant to meets the demands of current machinery.

The depleting trend of conventional, non-renewable has triggered research and development on alternative renewable energy. Vegetable-based oil products are one of the most promising sources of renewable energy in this century [10][21]. In terms of biodegradability vegetables oils has better properties compare to the mineral oil. Attention has been focused by many party to develop vegetable oils as an industrial lubricant and also biodiesel [19].

Nowadays the increasing concern of biodegradability product has impact to the increase of interest in using vegetable oils as a lubricant in industry as proposed by Golshokouh et al., [9]. Vegetable oils is unique because some of its properties cannot be found in the mineral oil, with a lot of possibilities [15].

Campanella et al, [4] stated that the increase in the use of petroleum-based products has caused the progressive depletion of the world reserves of fossil fuels and there are also concerns on their environmental impact. Many researchers, such as Erhan et al, [8], and Zulkifli et al, [30] agree that most of the lubricant nowadays are hazardous to the environment and cannot be dispose after use.

According to Jabal and friends, The advantages of using vegetable oil as a lubricant compare to other type of lubricant is they are less toxic and more important they are biodegradable [2][16]. Vegetable oils also a renewable source that easily to reproduce compare to the mineral based oil. Because of the high molecular weight of its triglyceride molecule, vegetable oil has a very low volatility. Vegetable oils also possess a good lubricity due to its polar ester groups that able to adhere to metal surface [4][8]. Having a high flash and fire point also one of the vegetable oils advantage, because of these properties vegetable oils is very suitable to be used in applications where fire or explosion has a possibility to propagate [6]. Zulkifli and friends state that the vegetable oil has a high viscosity index, which should be high enough to maintain the lubricating film thickness, and low enough to make sure that the oil can flow through all the engine parts. Besides that vegetable oil also has superior anticorrosion properties due to its metal surface affinity [24]

Low temperature performance is one of the weakness using vegetable oils to be a bio lubricant [14][23]. Vegetable oil become poor flow properties when it exposed to a lower temperature and become cloudiness and solidified upon a long term exposure [22]. Deliberate modification of the chemical structure of vegetable oils is a sound alternative to allow their direct use as lubricant base stocks [4][17].

Palm oil has been tested by several researchers for different engineering applications. Syahrullail and his colleagues investigated the characteristics of palm oil as a metal forming lubricant [25[26][27]. Besides that, palm oil was also investigated to be used as diesel engine and hydraulic fluid as proposed by Bari and Wan Nik respectively [1][29]. There are four major groups of palm oil that were investigated by the researchers around the world, namely 100% palm oil as a test lubricant [18][28], Uses palm oil as additives [5], Uses palm oil with additive [7] and Uses palm oil emulsion [11]. All of the research proved and found out that palm oil shows satisfactory results and has a bright future to be used widely in engineering applications. There is no argument on the performance of palm oil as lubricant. It has also been proven that palm oil has good performance in term of lubrication and has the potential to reduce the dependency on mineral based oil lubricants.

This research is to investigate the effect of the various percentage (w/w %) of pour point depressant (PPD) to the coefficient of friction and wear performance of the refine palm kernel oil (RBD PKO) under low starting temperature using four ball machine. The RBD PKO is a refined palm oil product that is solid at room temperature. The bench mark for the test is using mineral oil and also RBD PKO without PPD. The experiment is conducted following the standard ASTM D4172.

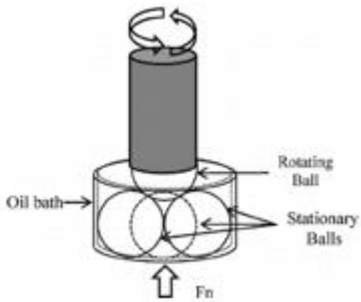

Figure 1: Schematic diagram of four ball tribotester

2. Experimental method

2.1 Apparatus

Four ball tribotester machine was used to conduct the experiment as shown in Figure 1, the machine is used to investigate the characteristic of the lubricant properties and the wear (Boelarge, 1993). The machine test is using four ball, where three balls at the bottom that is held by a ball pot and one at the top that held by the collector as shown in Figure 2. The lubricant is put at the ball pot together with the three ball, and the ball pot will press upward against the top ball that will rotate to a desired level of speed.

The important component of the experiment such as collect, oil cup assembly and ball bearing must be washed with acetone before been used to test it.

2.2 Lubricants

The based lubricant used were palm kernel oil. Malaysia has successful develop the refine of palm oil and one of the product id RBD palm kernel oil. RBD is means refine, bleaching and deodorised, which means that this oil has gone through a purifying process to vanish the unnecessary fatty acid and odour. Then it has also gone through a fractionation process to extract the palm kernel oil.

Table 1: Percentage of PPD in palm kernel oil and mineral oil

SAMPLE	PPD PERCENTAGE (%)
PKO	0
A2-5%	5
A2-10%	10
A2-20%	20
A2-30%	30

The lubricant used for this experiment were RBD palm kernel oil and RBD with addition of PPD (5, 10, 20 and 30%w/w). The PPD (A2) used were distribute from HB Laboratories. PPD is based on Alpha-olefin copolymer with heavy aromatic naphtha as it’s based. The PPD is used to reduce the pour point of the RBD palm kernel oil. The result obtain will be compared to the mineral oil as a benchmark. For every test of the machine, 10ml of sample will be used.

2.3 Low temperature ability of lubricants evaluation

Low temperature ability of lubricants are evaluated by using method of cooling the lubricant at certain temperature in the refrigerator for 1 days. Before lubricant are kept in the refrigerator, all lubricants are heating to 30 °C to ensure all lubricant in liquid state. Then all lubricant are kept in refrigerator with initial temperature set to 25°C. Temperature are dropped with interval 5 °C for each temperature drop

2.4 Test procedure

The test procedure will be follow the ASTM D4172 standard. Below the test condition for lubricity test using four-ball tribotester machine [38][39]

Table 3: the test condition

Starting Temperature	75˚C, 20˚C and 15˚C
Speed	1200rpm
Duration	60min
Load	40KG

For the test of wear scar diameter and also the CCD image. We need to use the specific CCD microscope and also measure the diameter using specific measurement soft wear. All of the test must be save for the result and the discussion.

3.0 Result and Discussion

The impacts of RBD palm kernel oil blended with PPD was examined and also characterised. The test results will show the performances of RBD palm kernel oil that blended with PPD in term of WSD, COF and also surface profile that will compare to pure RBD Palm Kernel Oil)

3.1 Lubricant Density and Kinematic Viscosity evaluation

The density test for all lubricants used in this research are tabulated as in Table 3.1. ASTM D1298 – 12b method is used to determine the density of the lubricant at the temperature of 25°C

Table 3.1: Density for All Lubricant Used in Research

Lubricant	Density @ 25°C, kg/cm^3
Palm Kernel Oil	0.91
A2-5%	0.915
A2-10%	0.915
A2-20%	0.92
A2-30%	0.92

For viscosity test method, viscometer rotor is used to evaluate its fluidity by turning the rotor at fixed rotated speed and at the same time lubricant is heated until 100 °C. The kinematic viscosity of tested lubricants are shown in Table 3.2. The viscosity index is calculated based on ASTM D2270

Table 3.2: Kinematic Viscosity of Tested Lubricants at Selected Temperatures

Temperature (˚C)	Kinematic Viscosity (mm^2/s)				
	Palm Kernel Oil	A2-5%	A2-10%	A2-20%	A2-30%
25	45.77	38.8	37.01	35.8	29.8
35	38.48	32.86	30.58	29.01	22.6
40	35.36	29.71	27.85	26.6	24.25
75	20.17	21.17	18.97	12.7	11.54
100	11.24	13.98	13.00	11.9	10.97
Viscosity Index	329.9	484.89	484.955	469.004	478.873

3.1 Low Temperature Ability Observation of a Lubricants

Palm Kernel oil, A2-5%, A2-10%, A2-20% and A2-30% are heated to 30˚C in order to remove the wax crystallize and then the temperature is lowered (25˚C, 20˚C and 15˚C) for one day to observe the capability of the sample to withstand in a lower temperature.

Table 3.3: Effect of PPD to the RBD PKO for different percentage of PPD on its pour point

Sample	Blend ratio (wt/wt)		Solid Phase Temperature (˚C)
	RBD PKO	PPD	
RBD PKO	100	0	25
A2-5%	95	5	20
A2-10%	90	10	20
A2-20%	80	20	15
A2-30%	70	30	15

From the result obtain we can see that at 25˚C the PKO liquid start to fully solidified, this show that the pour point of the pure RBD PKO cannot withstand at lower temperature without modifying it or adding any additive. At 15 ˚C, all sample PKO, A2-5%, and A2-10% were completely solidified except for A2-20% and A2-30% where the sample behave a liquid form but in waxy form

3.2 Coefficient of friction

The coefficient of friction is presented in figure 3.1 for sample pko, A2-5%, A2-10%, A2-20% and A2-30% at its liquid phase. From the data obtain it shows that the coefficient of friction is increasing as the temperature decrease for all sample. Adding the PPD will slightly increase the COF and A2-30% has the highest value of the COF for through the entire starting temperature. The increasing in COF is influenced by the sample kinematic viscosity, higher in kinematic viscosity will produce lower COF for each of the sample lubricant that been test. This is supported by (Minami I, 2009) [32].

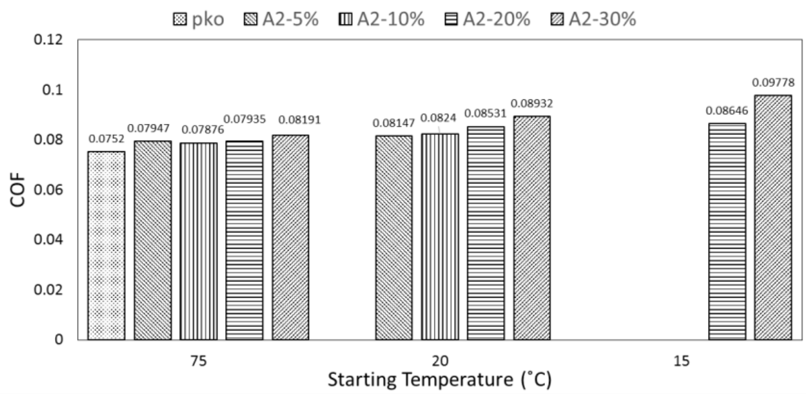

Figure 3.1: Coefficient of friction (COF)

According to Clark et al., [37] viscosity of the fuel decreases with increasing of temperature. Another possible interpretation given by Masjuki et al., [35] is that the lower boundary effect and/or breakdown of boundary lubrication is due to the lower viscosity. According to Sharma et al. the fatty acid chain are adsorbed to metal surfaces, thus permitting monolayer film formation with the hydrocarbon end of fatty acids oriented away from the metal surface. The fatty acid chain thus offers a sliding surface that prevents the direct metal-to-metal contact.

Masjuki et al.,[18] stated that the lower boundary effect and/or breakdown of boundary lubrication is due to the lower viscosity. According to Sharma et al. the fatty acid chain are adsorbed to metal surfaces, thus permitting monolayer film formation with the hydrocarbon end of fatty acids oriented away from the metal surface. The fatty acid chain thus offers a sliding surface that prevents the direct metal-to-metal contact.

3.3 Wear Scar Diameter

From this research point of view, the lubricity performance of an oils can say are good when it can have lower value of wear scar diameter. Figure 3.2 illustrates the average wear scar diameter for pko, A2-5%, A2-10%, A2-20% and A2-30% at its liquid phase. Although adding the PPD will increase the

COF, but in terms of WSD adding PPD has also reduce the scar of the ball when compare to pko. In general we can see that the WSD is increase as the starting temperature is lower. However the result obtain is opposed by Maleque et al.,(2000) [34] that state at higher wear will produced at higher temperature

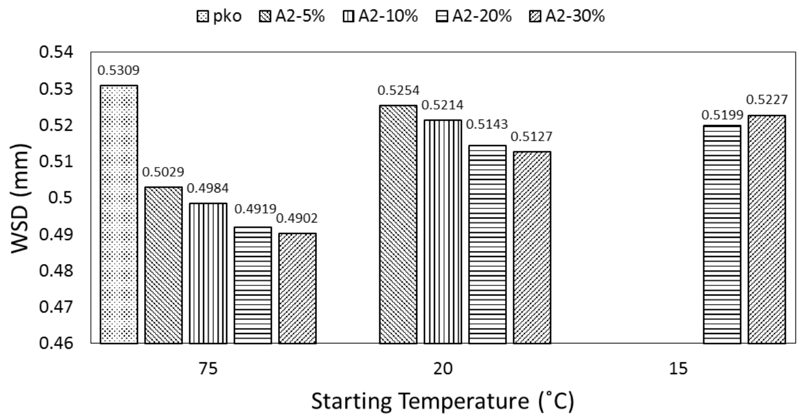

Figure 3.2: Wear Scar Diameter (WSD)

Test on starting point 75˚C shows adding PPD reduce the WSD with A2-30% has the lowest WSD. The WSD test on the 20˚C and 15˚C is increase for all sample, this shows low temperature performance is reduce when exposed in lower temperature. This is maybe due to the chemical attack on the rubbing surfaces of fatty acid as proposed by Bowden & Tabor, (2001) [36]. Lower in WSD at higher temperature also stated by Masjuki and Maleque *(1996*) [35] claimed that this phenomenon could be related to the thinning of the fatty acid thin film, which acts as an effective barrier against metal-to-metal contact.

From the figure 3.2 the wear scar diameter at 20ºC shows that sample with 30% PPD has the lowest wear scar diameter (0.5127mm) and sample with 5% PPD shows the highest value of the wear scar diameter (0.5254mm), the graph trend shows adding PPD will reduce the wear scar diameter at this temperature. However at 15°C temperature the value of sample with 20% PPD (0.5199mm) has lower wear scar diameter compare to A2-30% (0.5227mm).

3.4 Surface Roughness

Figure 3.3 shows the relationship of starting temperature with the surface roughness for pko, A2-5%, A2-10%, A2-20% and A2-30%. The grooves on the surface of ball bearing will affect the surface roughness value, where the smooth surface roughness has a shallow grooves. From the graph plotted the value of surface roughness is increasing as the starting ting temperature lower.

From the data obtain the value sample with 20%PPD has the lowest surface roughness at 20ºC (0.116) and A2-5% has the highest roughness that is 0.138, this shows that the sample that can maintain its liquid phase at lower temperature can help in reducing the surface roughness of the sample at low temperature test. The sample with 30% PPD shows increase in surface roughness compare to sample with 20% PPD at all low temperature test, although the sample has successfully withstand at 15°C low temperature lubricity test, but the increasing in PPD percentage in sample will reduce the present of the fatty acid inside the palm kernel oil that can help the lubricant to improve the lubricity performance as proposed by Lawal et al., (2008)[40].

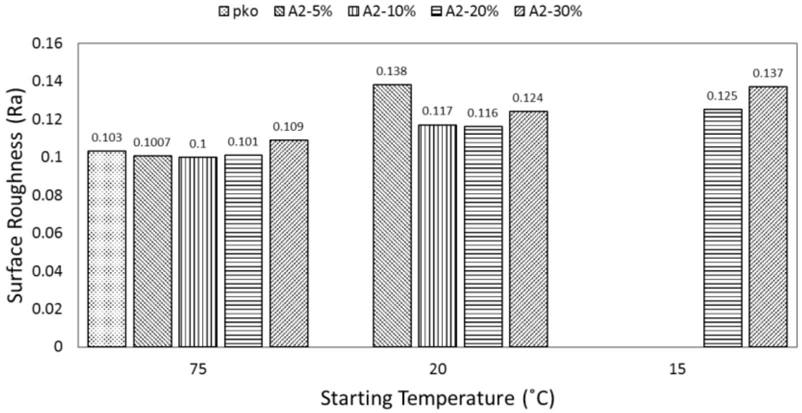

Figure 3.3: Surface Roughness

3.5 Worn Surface Characteristic

Figure 3.4, 3.5 and 3.6 shows the representative wear scar for all sample at different starting temperature test. At starting temperature 75˚C it clearly showed that the WSD is decrease as PPD percentage is increase. At 20˚C starting temperature A2-10% has the highest WSD compare to other sample and when observing 15˚C starting temperature, A2-30% is higher WSD compare to A2-20%

From figure 3.4 with all sample at high temperatures, the lubricant chain started to break down and metal-to-metal contact occurred. In addition, the wear particles that existed between the mating surfaces of the ball bearing caused adhesive wear. But at A2-30% there is no major adhesive wear occur. At a low working temperature, a thin lubricant film with parallel grooves formed to prevent metallic contact and create smooth surface regions. Some of the grooves were deep and the others were shallow grooves in between. In this region, abrasion was seen as the dominant wear mechanism. At a high working temperature, the thin lubricant films were broken and adhesive wear appeared to be predominant.

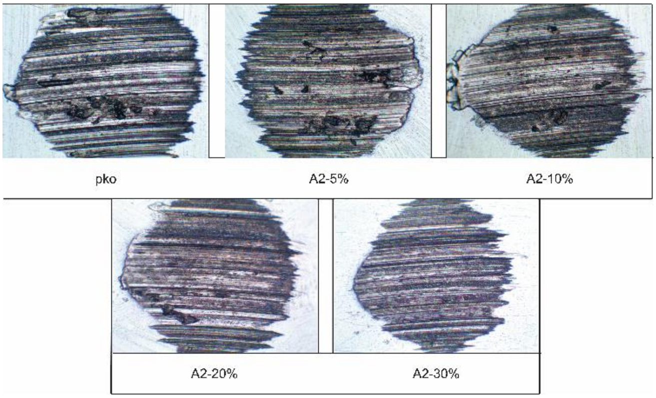

Figure 3.4: Starting temperature 75˚C

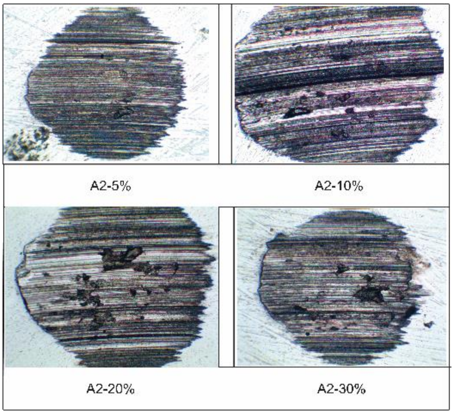

Figure3.5: Starting temperature 20˚C

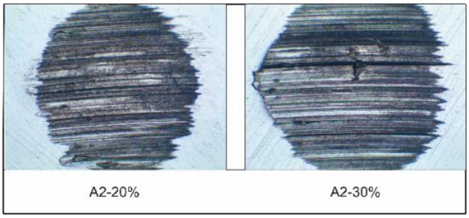

Figure 3.6: Starting Temperature 15˚C

CONCLUSION

The tribological performance of sample pko, A2-5%, A2-10%, A2-20% and A2-30% was evaluated using fourbal tribotester at different starting temperature. The finding can be summarized as follows

1. Low temperature test shows that adding PPD has successful improve the palm kernel oil low temperature performance with A2-20% and A2-30% can withstand lower temperature (15˚C) compare to A2-5% and A2-10% (20˚C)
2. The coefficient of friction is increase as the starting temperature is lower for pko, A2-5%, A2-10%, A2-20% and A2-30%. A2-30% has highest coefficient of friction value through the entire test.
3. For wear scar diameter it can see that palm kernel oil having high wear scar compare to A2-5%, A2-10%, A2-20% and A2-30%. In general the wear scar also shows increasing trend as starting temperature is lower. At 75˚C the trend shows that adding PPD successful improve the lubricity performance in terms of wear scar diameter
4. The low starting temperature slightly has effect the lubricity performance in terms of surface roughness. At 75˚C the surface roughness is decreasing from A2-5% to A2-20%
5. Abrasive wear was the dominant wear mechanism for all sample at all starting temperature and a few adhesive wear were spotted at all test

Acknowledgement

The authors would like to express their thanks to the Research Management Centre (RMC) of Universiti Teknologi Malaysia for the Research University Grant, GUP (17H96) and Ministry of Education of Malaysia and Ministry of Higher Education for their support.

References

[1] Bari, S., Lim, T. H., & Yu, C. W. (2002). Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. Renewable Energy, 27(3), 339–351. http://doi.org/10.1016/S0960-1481(02)00010-1

[2] Battersby, N. S. (2000). The biodegradability and microbial toxicity testing of lubricants–some recommendations. Chemosphere, 41(7), 1011-1027

[3] Boerlage, G. (1993). Four-ball Testing Apparatus for extreme-pressure Lubricants. Engineering, 44-47.

[4] Campanella, A., Rustoy, E., Baldessari, A., & Baltan, M. A. (2010). Lubricants from chemically modified vegetable oils. Bioresource Technology, 101(1), 245–254. http://doi.org/10.1016/j.biortech.2009.08.035

[5] Castro, W., Weller, D. E., Cheenkachorn, K., & Perez, J. M. (2005). The effect of chemical structure of basefluids on antiwear effectiveness of additives. Tribology International, 38(3), 321-326.

[6] Cermak, S. C., Biresaw, G., Isbell, T. A., Evangelista, R. L., Vaughn, S. F., & Murray, R. (2013b). New crop oils-Properties as potential lubricants. Industrial Crops and Products, 44, 232–239. http://doi.org/10.1016/j.indcrop.2012.10.035

[7] Chew, T. L., & Bhatia, S. (2009). Effect of catalyst additives on the production of biofuels from palm oil cracking in a transport riser reactor. Bioresource Technology, 100(9), 2540–2545. http://doi.org/10.1016/j.biortech.2008.12.021

[8] Erhan, S. Z., Sharma, B. K., & Perez, J. M. (2006). Oxidation and low temperature stability of vegetable oil-based lubricants. Industrial Crops and Products, 24(3), 292–299. http://doi.org/10.1016/j.indcrop.2006.06.008

[9] Golshokouh, I., Golshokouh, M., Ani, F. N., Kianpour, E., & Syahrullail, S. (2013). Investigation of physical properties for jatropha oil in different temperature as lubricant oil. *Life Science Journal*, *10*(8s).

[10] Hafis, S. M., Ridzuan, M. J. M., Farahana, R. N., Ayob, A., & Syahrullail, S. (2013). Paraffinic mineral oil lubrication for cold forward extrusion: Effect of lubricant quantity and friction. Tribology International, 60, 111-115

[11] Husnawan, M., Masjuki, H. H., Mahlia, T. M. I., & Saifullah, M. G. (2009). Thermal analysis of cylinder head carbon deposits from single cylinder diesel engine fueled by palm oil-diesel fuel emulsions. Applied Energy, 86(10), 2107–2113. http://doi.org/10.1016/j.apenergy.2008.12.031

[12] Ing, T. C., Rafiq, A. K. M., Azli, Y., & Syahrullail, S. (2012). Tribological behaviour of refined bleached and deodorized palm olein in different loads using a four-ball tribotester. Scientia Iranica, 19(6), 1487-1492.

[13] Jabal, M. H., Ani, F. N., & Syahrullail, S. (2014). The tribological characteristic of the blends of rbd palm olein with mineral oil using four-ball tribotester. Jurnal Teknologi (Sciences and Engineering), 69(6), 11–14. http://doi.org/10.11113/jt.v69.3232

[14] Kassfeldt, E., & Dave, G. (1997). Environmentally adapted hydraulic oils.Wear, 207(1), 41-45

[15] Lathi, P. S., & Mattiasson, B. (2007). Green approach for the preparation of biodegradable lubricant base stock from epoxidized vegetable oil. Applied Catalysis B: Environmental, 69(3-4), 207–212. http://doi.org/10.1016/j.apcatb.2006.06.016

[16] Lawate, S. (2002). Environmentally-friendly hydraulic fluids. Bio-based Industrial Fluids and Lubricants, 35-45

[17] Lv, P., Cheng, Y., Yang, L., Yuan, Z., Li, H., & Luo, W. (2013). Improving the low temperature flow properties of palm oil biodiesel: Addition of cold flow improver. Fuel Processing Technology, 110, 61–64.

[18] Masjuki, H. H., Maleque, M. A., Kubo, A., & Nonaka, T. (1999). Palm oil and mineral oil based lubricants—their tribological and emission performance. Tribology International, 32(6), 305–314. http://doi.org/10.1016/S0301-679X(99)00052-3

[19] Metzger, J. O. (2009). Fats and oils as renewable feedstock for chemistry.European Journal of Lipid Science and Technology, 111(9), 865-876.

[20] Ming, T. C., Ramli, N., Lye, O. T., Said, M., & Kasim, Z. (2005). Strategies for decreasing the pour point and cloud point of palm oil products. European Journal of Lipid Science and Technology, 107(7-8), 505–512. http://doi.org/10.1002/ejlt.200400944

[21] Pradhan, A., Shrestha, D. S., McAloon, A., Yee, W., Haas, M., & Duffield, J. A. (2011). Energy life-cycle assessment of soybean biodiesel revisited.Transactions of the ASABE, 54(3), 1031-1039.

[22] Quinchia, L. A., Delgado, M. A., Franco, J. M., Spikes, H. A., & Gallegos, C. (2012). Low-temperature flow behaviour of vegetable oil-based lubricants. Industrial Crops and Products, 37(1), 383–388. http://doi.org/10.1016/j.indcrop.2011.12.021

[23] Rhee, I. S., Velez, C., & Von Bernewitz, K. (1995). Evaluation of Environmentally Acceptable Hydraulic Fluids (No. TARDEC-TR-13640). TACOM RESEARCH DEVELOPMENT AND ENGINEERING CENTER WARREN MI.

[24] Syahrullail, S., Wira, J. Y., Wan Nik, W. B., & Fawwaz, W. N. (2013). Friction characteristics of RBD palm olein using four-ball tribotester. Applied Mechanics and Materials, Vol. 315, pp. 936-940.

[25] Syahrullail, S., Azwadi, C. S. N., & Ing, T. C. (2011b). The metal flow evaluation of billet extruded with RBD palm stearin. International Review of Mechanical Engineering, 5(1), 21-27.

[26] Syahrullail, S., Nakanishi, K., & Kamitani, S. (2005). Investigation of the effects of frictional constraint with application of palm olein oil lubricant

and paraffi n mineral oil lubricant on plastic deformation by plane strain extrusion. Toraibarojisuto/Journal of Japanese Society of Tribologists, 50(12), 877–885.

[27] Syahrullail, S., Zubil, B. M., Azwadi, C. S. N., & Ridzuan, M. J. M. (2011a). Experimental evaluation of palm oil as lubricant in cold forward extrusion process. International Journal of Mechanical Sciences, 53(7), 549–555. http://doi.org/10.1016/j.ijmecsci.2011.05.002

[28] Tiong, C. I., Azli, Y., Kadir, M. R. A., & Syahrullail, S. (2012). Tribological evaluation of refined, bleached and deodorized palm stearin using four-ball tribotester with different normal loads. Journal of Zhejiang University Science A, 13(8), 633-640.

[29] Wan Nik, W. B., Ani, F. N., & Masjuki, H. H. (2005). Thermal stability evaluation of palm oil as energy transport media. Energy Conversion and Management, 46(13-14), 2198–2215. http://doi.org/10.1016/j.enconman.2004.10.008

[30] Zulkifli, N. W. M., Kalam, M. A., Masjuki, H. H., Shahabuddin, M., & Yunus, R. (2013). Wear prevention characteristics of a palm oil-based TMP (trimethylolpropane) ester as an engine lubricant. Energy, 54, 167–173. http://doi.org/10.1016/j.energy.2013.01.038

[31] Golshokouh, I., Syahrullail, S., Ani, F. N., & Masjuki, H. H. (2013). Investigation of Palm Fatty Acid Distillate as an Alternative Lubricant of Petrochemical Based Lubricants, Tested at Various Speeds. International Review of Mechanical Engineering (IREME), 7(1), 72-80..

[32] Minami, I. (2009). Ionic liquids in tribology. Molecules, 14(6), 2286-2305

[33] Bowden, F. P., & Tabor, D. (2001). The friction and lubrication of solids (Vol. 1). Oxford university press.

[34] Maleque, M. A., Masjuki, H. H., & Haseeb, A. S. M. A. (2000). Effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant. Wear, 239(1), 117-125.

[35] Masjuki, H. H., & Maleque, M. A. (1996). The effect of palm oil diesel fuel contaminated lubricant on sliding wear of cast irons against mild steel. Wear, 198(1), 293-299.

[36] Bowden, F. P. and Tabor, D. (2001), The Nature of Metallic Wear: The Friction and Lubrication of Solids, Oxford University Press: Oxford, UK

[37] Clark, S. J., dos Santos, A. M., de Souza, G. R., and Polito, W. L. (1984), "Methyl and Ethyl Soybean Esters as Renewable Fuels for Diesel Engines," Journal of the American Oil Chemists Society, 61, pp 1632–1638.

[38] Aiman, Y., & Syahrullail, S. (2017). Development of palm oil blended with semi synthetic oil as a lubricant using four-ball tribotester. Jurnal Tribologi, 13, 1-20.
[39] Farhanah, A. N., & Syahrullail, S. (2016). Evaluation of lubrication performance of RBD palm stearin and its formulation under different applied loads. Jurnal Tribologi, 10, 1-15.
[40] Lawal, O. S., Lechner, M. D., & Kulicke, W. M. (2008). The synthesis conditions, characterizations and thermal degradation studies of an etherified starch from an unconventional source. Polymer Degradation and Stability, 93(8), 1520-1528.