

TRIBOLOGICAL PERFORMANCE ANALYSIS  
OF NANOCELLULOSE-AL<sub>2</sub>O<sub>3</sub>-ENGINE OIL

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## **SUPERVISOR'S DECLARATION**

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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TRIBOLOGICAL PERFORMANCE ANALYSIS OF NANOCELLULOSE- $\text{Al}_2\text{O}_3$ -  
ENGINE OIL

AMIRRUDDIN BIN ABDUL KADIR

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## ABSTRAK

Dalam kajian semasa, pelincir nano memainkan peranan penting dalam semua komponen mesin untuk menghindari kehausan dan kakisan akibat gerakan relatif antara permukaan yang bersentuhan seperti alas bebola, aci sesondol, omboh, kotak gear, skru, kerja logam, cecair, gear, dan dalam penghawa dingin automotif. Memandangkan undang-undang alam sekitar sentiasa mengalami peningkatan pembaharuan, industri pelincir telah berusaha keras untuk menghasilkan pelincir alternatif yang mesra alam sekitar untuk enjin pembakaran dalaman. Dalam menangani cabaran ini, kegunaan pelincir mestilah mematuhi piawaian alam sekitar dan dalam pada masa yang sama mengekalkan prestasi pelincir yang baik. Tesis ini mengkaji keupayaan tribologi bagi pelincir hibrid dalam meningkatkan prestasi pelincir nano dengan melakukan penyelidikan dengan menggunakan Nano Selulosa (CNC) dan Aluminium Oksida ( $Al_2O_3$ ) yang merupakan pelincir nano hibrid, sebagai penyelesaian alternatif yang memastikan pengurangan kelakuan tribologi terhadap pelincir pepejal dan cecair serta meningkatkan jangka hayat komponen mekanikal yang mana CNC adalah konduktor haba yang baik berdasarkan susunan strukturnya yang membolehkan konduksi haba. Pelincir nano berhibrid dengan nisbah yang berbeza adalah sebagai aditif di dalam minyak enjin, yang digunakan untuk mengawalselia sifat-sifat fizikal-termo seperti mengurangkan kesan COF dan WR yang menggunakan bahan omboh yang sama. Pelincir nano disediakan dengan beberapa nisbah kepekatan seperti 0.3 %, 0.5 % dan 0.7 % yang dibandingkan dengan minyak asas 10W-40 dan diukur nilai termo fizikalnya pada beberapa nilai suhu iaitu 30 °C, 50 °C dan 70 °C. Konduksi haba dan kelikatan dinamik menunjukkan tindak balas yang positif kepada perbandingan dengan minyak asas di mana kekonduksian terma meningkat apabila suhu meningkat manakala kelikatan dinamik pula berkurangan apabila suhu meningkat. Pelincir nano berhibrid mempunyai peningkatan 18.09 % pengkonduksian termal yang tertinggi berbanding dengan 10W-40 minyak asas. Sementara pelincir nano pula memberikan peningkatan 21.8 % kelikatan dinamik yang paling rendah berbanding dengan 10W-40 minyak asas. Berdasarkan kepada semua ujian sifat asas termal, pelincir nano berhibrid dengan kepekatan 0.5 % memberikan keputusan yang terbaik. Pemerhatian secara visual memaparkan terdapat sedikit mendapan tetapi ianya tidak signifikan dan sampel-sampel dianggap stabil setelah melalui ujian kestabilan selama dua bulan. Hasil pengiraan nilai optimum mendapati bahawa pelincir nano hibrid (CNC+ $Al_2O_3$ ) menghasilkan geseran yang minimum, kurang kesan lusuh dan ia boleh bertahan pada beban yang tinggi. Berdasarkan hasil penyelidikan, kesimpulannya semua objektif penyelidikan telah tercapai. Campuran hibrid Nano partikel  $Al_2O_3$  + CNC boleh digunakan sebagai pelincir tambahan dalam mengurangkan COF (16 %) dan WR (71 %). Selain itu, kajian ini juga menunjukkan bahawa penggunaan partikel  $Al_2O_3$  turut berpotensi untuk menambah baik minyak pelincir pada ketahanan tinggi melalui mereplikasi setiap pengukuran ujikaji terhadap enjin pembakaran dalaman pada kereta sebenar.

## ABSTRACT

In the current studies, the nano-lubricants have been the vital role in all machine components in preventing wear and tear due to relative motion between the contact surfaces such as bearings, camshaft, piston, gearbox, lead screw, metal working, fluids, gears, and in automotive air-conditioning. Given continuous environmental legislation, the lubrication industry has been striving to produce environmentally suitable lubrication alternatives for internal combustion engines. Addressing this challenge requires the use of lubricants that conforms to environmental standards while maintaining excellent lubrication performance. This thesis investigates the tribological viability of hybrid lubricants in improving the performance of the nano-lubricants, research is done by using Nano cellulose (CNC) and Aluminium Oxide ( $\text{Al}_2\text{O}_3$ ) as the hybrid nano-lubricant, being as the promising alternative and solution for tribological behaviour of both solid and liquid lubrication and extends the life of the mechanical components which CNC is well known as a good heat conductor due to its structural arrangement that allow to conduct heat. The hybrid of nano-lubricant with different ratios as additives in engine oil is then used to conduct thermo-physical properties as to reduce the COF and WR of similar piston material. The nano-lubricant is prepared with multiple ratios 0.3 %, 0.5 % and 0.7 % concentration which were compared to base oil 10W-40 and tested for properties at 30 °C, 50 °C and 70 °C. Thermal conductivity and dynamic viscosity showed a positive response to the comparison with base oil as for thermal conductivity, it increases as temperature increases while dynamic viscosity reduces as the temperature increases. Nano-hybrid lubricant has the highest thermal conductivity enhancement compared with 10W-40 base oil at 18.09 %. Meanwhile, nano-lubricant exhibit lowest enhancement of dynamic viscosity compared with 10W-40 base oil at 21.8 %. As per over all property test, 0.5 % nano-hybrid lubricant concentration has the best result. The visual observation displayed a very small sedimentation which is insignificant and samples are considered stable throughout the stability test done for two months. Optimisation finding that hybrid (CNC+ $\text{Al}_2\text{O}_3$ ) nano-lubricant produced less friction, less wear effect and it can stand high load. Based on the research finding, it can be concluded that the research objectives are achieved. The hybrid  $\text{Al}_2\text{O}_3$  nanoparticles + CNC can be used as additive in lubricant in reducing the COF (16 %) and WR (71 %). Moreover, this study has shown that the used of the  $\text{Al}_2\text{O}_3$  nanoparticles have the potential to improvise the lubricant for better durability to apply in the system replicating an internal combustion engine of an actual car.

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## LIST OF ABBREVIATIONS

Ag	Silver
Al	Aluminum
Al/Sn	Aluminum-Tin
Al <sub>2</sub> O <sub>3</sub>	Aluminum Oxide
Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>	Aluminum Oxide-Silicone Oxide
AW	Anti-wear
APS	Average particle size
C	Carbon
C <sub>D</sub>	Drag Coefficient
C <sub>f</sub>	Coefficient Friction Factor
Co	Cobalt
CO <sub>2</sub>	Carbon Dioxide
CNC	Nano cellulose
Cr	Chromium
Cu	Copper
COF	Coefficient of Friction
CuO	Copper (II) Oxide
Dh	Hydraulic diameter
DV	Dynamic Viscosity
EDX	Energy-dispersive X-ray Spectroscopy
Ep	Extreme pressure
Fe	Iron
FESEM	Field Emission Scanning Electron Microscopy
g	Gravity
h	Height
H <sub>2</sub>	Hydrogen
He	Helium
IC	Internal combustion
IR	Infrared
L	Length
LOF	Lack of Fit

Mg	Magnesium
MoDTC	Molybdenum Dialkylthiocarbamate
MOO	Multi-Objective Optimization
MoS <sub>2</sub>	Molybdenum Disulfide
MoS <sub>2</sub> /TiO <sub>2</sub>	Molybdenum Disulphide-Titanium Dioxide
Ni	Nickel
O <sub>2</sub>	Oxygen
OM	Optical Microscopy
P	Phosphorus
p	Hydrostatic pressure
Δp	Pressure drop
Pb	Lead
PAGs	Polyalkylene Glycols
r	Radius of nanoparticle
Ra	Average roughness
Re	Reynold Number
Rq	Mean root mean square roughness
RSM	Response Surface Methodology
S	Sulfur
Si	Silicon
SEM	Scanning Electron Microscope
SiO <sub>2</sub>	Silicon Dioxide, Silica
Ti	Titanium
TAG	Triacylglycerol
TAN	Total acid number
TEM	Transmission Electron Microscopy
TiO <sub>2</sub>	Titanium Dioxide
TiO <sub>2</sub> /SiO <sub>2</sub>	Titanium Silicon Oxide, Titanium Silicate, Silicon Titanate
UV-vis	Ultraviolet–visible
v <sub>z</sub>	settling velocity
VI	Viscosity Index
W	Wide

$WS_2$	Tungsten Disulfide
WR	Wear Rate
XPS	X-ray Photoelectron Spectroscopy
ZnO	Zinc Oxide
$ZrO_2$	Zirconium Dioxide
$ZnAl_2O_4$	Zinc Aluminate
$ZrO_2/SiO_2$	Zirconia Oxide-Silica Oxide
$\rho_{NP}$	Density of nanoparticles
$\rho_F$	Density of fluid
$\tau$	Fluid viscosity
$\tau_w$	Shear stress
$\mu$	Viscosity of the fluid

## REFERENCES

- Abdullah, M. I. H. C., Abdollah, M. F., Amiruddin, H., Tamaldin, N., and Nuri, N. R. M. (2014). Effect of hBN /Al<sub>2</sub>O<sub>3</sub> nanoparticle on the tribological performance of engine oil. *Jurnal Teknologi (Sciences and Engineering)*, 66(3), 1–6.
- Abbasi, S. M., Rashidi, A., Nemati, A., and Arzani, K. (2013). The effect of functionalisation method on the stability and the thermal conductivity of nanofluid hybrids of carbon nanotubes/gamma alumina. *Ceramics International*, 39(4), 3885–3891.
- Ahmadi, H., Etefaghi E., Rashidi A., Nouralishahi A. and Mohtasebi S. (2013). Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. *International Communications in Heat and Mass Transfer*, 46, 142-147.
- Agarwal, G., Patnaik, A., and Sharma, R. K. (2013). Parametric optimization and three-body abrasive wear behavior of Sic filled chopped glass fiber reinforced epoxy composites. *international journal of composite material*, 2, 32-38.
- Akchurin, A. and Bosman R. (2017). A Deterministic Stress-Activated Model for Tribo-Film Growth and Wear Simulation. *Tribology Letters*, 65(2), 59.
- Akchurin, A., Bosman R., Lught, P. M., Mark, V. D. (2015). On a model for the prediction of the friction coefficient in mixed lubrication based on a load-sharing concept with measured surface roughness. *Tribology Letters*, 59(1), 19.
- Akhavan, O., Abdolahad M, Esfandiar A.(2010). Photodegradation of graphene oxide sheets by TiO<sub>2</sub> nanoparticles after a photocatalytic reduction. *The Journal of Physical Chemistry C*, 114(30), 12955-12959.
- Aldrich, B. (1995). ABC's of AFV's: A Guide to Alternative Fuel Vehicles. DIANE Publishing.
- Ali, H.M., Ali, H., Liaquat, H., Bin Maqsood, H.T. and Nadir, M.A. (2015). Experimental investigation of convective heat transfer augmentation for car radiator using ZnO-water nanofluids. *Energy*, 84, 317–324.

- Ali, H. M., Sajid, M. U. and Arshad, A. (2017). Heat transfer applications of TiO<sub>2</sub> nanofluids. *Application of Titanium Dioxide*, InTech.
- Ali, M. K. A., Xianjun, H., Mai, L., Qingping, C., Turkson, R. F., and Bicheng, C. (2016). Improving the tribological characteristics of piston ring assembly in automotive engines using Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> nanomaterials as nano-lubricant additives. *Tribology International*, 103, 540-554.
- Alias, A. A., Kinoshita, H., Nishina, Y., and Fujii, M. (2016). Dependence of pH level on tribological effect of graphene oxide as an additive in water lubrication. *Journal of Automotive and Mechanical Engineering (IJAME)*, 13(1), 3150-3156. doi:<http://dx.doi.org/10.15282/ijame.13.1.2016.2.0262>
- Alves, S. M., Barros, B. S., Trajano, M. F., Ribeiro, K. S. B., and Moura, E. (2013). Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions. *Tribology International*, 65, 28-36.
- Anders E. K. (2017). *Friction - Positive or Negative in Automated Production Flow Solution*. Retrieved from <http://blog.flexlink.com/friction-positive-or-negative-in-automated-production-flow-solutions/>
- Andersson, P., Jaana, T. and Sandström, C. (2002). Piston ring tribology. A literature survey. VTT Tiedotteita-Research Notes, 2178(1).
- A&D Instruments Limited. (2016). GR-series weighing scale. Retrieved from <http://www.andweighing.co.uk/product/gr-series>
- A&D Instruments Limited. (2017). FX-300i Precision Balance. Retrieved from <https://www.andweighing.com.au/products-service/reloading/fx-300i>
- Arshad, A., Ali, H.M., Ali, M. and Manzoor, S. (2017). Thermal performance of phase change material (PCM) based pin-finned heat sinks for electronics devices: Effect of pin thickness and PCM volume fraction, *Applied Thermal Engineering*, 112, 143–155.
- Asadi, A., Asadi, M., Rezaniakolaei, A., Rosendahl, L .A., Afrand, M., and Wongwises, S. (2018). Heat transfer efficiency of Al<sub>2</sub>O<sub>3</sub>-MWCNT/thermal oil hybrid nanofluid as a cooling fluid in thermal and energy management applications: An

experimental and theoretical investigation. *International Journal of Heat and Mass Transfer*, 117, 474–486.

- Ashraful, A. M., Masjuki, H.H., Kalam, M.A., Rizwanul Fattah, I.M., Imtenan, S., Shahir, S.A. and Mobarak, H.M. (2014). Production and comparison of fuel properties, engine performance, and emission characteristics of biodiesel from various non-edible vegetable oils: a review. *Energy Conversion and Management*, 80, 202-228.
- Askhadullin, R. S., Martynov, P N, Yuditsev, P. A., Simakov, A. A., Chaban, A. Y., Matchula, E. A. and Osipov, A. A. (2008). Liquid metal based technology of synthesis of nanostructured materials (by the example of oxides). These materials properties and applications areas. *Journal of Physics: Conference Series*, IOP Publishing, 98(072012).
- Aslan, N., and Cebeci, Y. (2007). Application of Box-Behnken design and response surface methodology fo modeling of some Turkish coals. *Fuel*, 90-97.
- Asrul, M., Zulkifli, N. W. M., Masjuki, H. H., and Kalam, M. A. (2013). Tribological properties and lubricant mechanism of nanoparticle in engine oil. *Procedia Engineering*, 320-325.
- Astray, G., Gullón, B., Labidi, J., and Gullón, P. (2016). Comparison between developed models using response surface methodology (RSM) and artificial neural networks (ANNs) with the purpose to optimize oligosaccharide mixtures production from sugar beet pulp. *Industrial Crops and Products*, 92, 290-299. doi:<http://dx.doi.org/10.1016/j.indcrop.2016.08.011>
- Atmanlı, A., Yüksel, B., İleri, E., and Deniz Karaoglan, A. (2015). Response surface methodology based optimization of diesel–n-butanol –cotton oil ternary blend ratios to improve engine performance and exhaust emission characteristics. *Energy Conversion and Management*, 90, 383-394.
- Bao-Sen, Z., Bin-Shi, X., Yi, X., Fei, G., Pei-Jing, S., and Yi-Xiong, W. (2011). CU nanoparticle effect on the tribological properties of hydrosilicate powders as lubricant additive for steel-steel contacts. *Tribological International*, 878-886.
- Battez, H. A., González, R., Felgueroso, D., Fernández, J. E., del Rocío Fernández, M., García, M. A., and Peñuelas, I. (2007). Wear prevention behaviour of nanoparticle suspension under extreme pressure conditions. *Wear*, 263(7–12), 1568-1574.



- Battez, A. H., R.Gonzalez, J.L., Viesca, J.E., Fernandez, Fernandez, J. M. D., Machado, A., Chou, R. and Riba, J. (2008). CuO, ZrO<sub>2</sub> and ZnO nanoparticles as antiwear additive in oil lubricants. *Wear*, 265(3-4), 422-428.
- Bayir, Y., Halici, Z., Keles, M. S., Colak, S., Cakir, A., Kaya, Y., and Akcay, F. (2011). Helichrysum plicatum DC. subsp. plicatum extract as a preventive agent in experimentally induced urolithiasis model. *Journal of ethnopharmacology*, 138(2), 408-414.
- Bell, J. (1993). *Engine lubricants*. Tribology Series. Elsevier, 26, 287-301.
- Bhatt I., and Tripathi B. N. (2011). Interaction of engineered nanoparticles with various components of the environment and possible strategies for their risk assessment. *Chemosphere*, 82(3), 308–317
- Bhushan B. (2004). *Micro/Nanotribology Studies Using Scanning Probe Microscopy*. In: Applied Scanning Probe Methods. NanoScience and Technology. Springer, Berlin, Heidelberg
- Bijwe, J., Garg, A., and Gandhi, O. P. (2000). Reassessment of engine oil periodicity in commercial vehicles. *Tribology and Lubrication Technology*, 56(1), 23.
- Boluk, Y., Lahiji, R., Zhao, L. Y., and McDermott, M. T. (2011). Suspension viscosities and shape parameter of cellulose nanocrystals (CNC). *Colloids and Surface. A: Physicochemical and Engineering Aspects*, 377(1-3), 297-303.
- Bryan, G., Chowdhury, S., Mobarak, A. M. (2014). Underinvestment in a profitable technology: The case of seasonal migration in Bangladesh. *Econometrica*, 82(5), 1671-1748.
- Bezerra, M. A., Santelli, R. E., Oliveira, E. P., Villar, L. S., and Escaleira, L. A. (2008). Response surface methodology (RSM) as a tool for optimization in analytical chemistry. *Talanta*, 76(5), 965-977.
- Cai-xiang, G., Guan-jun, Z., Lei, L., Xiao-yu, T., and Guang-yao, Z. (2009). Tribological effect of xide base nanoparticle in lubricating oils. *Journal of Marine Science and Application*, 8(1), 71-76.

- Cesur, I., Ayhan, V., Parlak., A., Savas, O., and Aydin, Z. (2014). The Effects of Different Fuels on Wear between Piston Ring and Cylinder. *Advances in Mechanical Engineering*, 2014(503212): 8 pages <http://dx.doi.org/10.1155/2014/503212>
- Chang, B. P., Akil, H. M., Nasir, R. B., and Khan, A. (2015). Optimization on wear performance of UHMWPE composites using response surface methodology. *Tribology International*, 252-262.
- Choi, S. U. S. and Eastman, J. A. (1995). Enhancing thermal conductivity of fluids with nanoparticles. *Conference: International Mechanical Engineering Congress and Exhibition*, San Francisco, CA, United states, 12–17 November, ASME, San Francisco. 99–105.
- Choi, Y., Lee, C., Hwang, Y., Park, M., Lee, J., Choi, C. and Jung, M. (2009). Tribological behaviour of copper nanoparticles as additive in oil. *Current applied physics*, 124-127.
- Chou, R., Battez, A. H., Cabello, J. J., Viesca, J. L., Osorio, A., and Sagastume, A. (2010). Tribological behavior of polyalphaolefin with the addition of nickel nanoparticles. *Tribology International*, 43(12), 2327-2332.
- Das, P. K., Mallik, A.K., Ganguly, R. and Santra, A.K. (2016). Synthesis and characterization of TiO<sub>2</sub>-water nanofluids with different surfactants. *International Communications in Heat and Mass Transfer*, 75 341–348.
- Demas, N. G., Timofeeva, E. V., Routbort, J. L. and Fenske, G. R. (2012). Tribological effects of BN and MoS<sub>2</sub> nanoparticles added to polyalphaolefin oil in piston skirt/cylinder liner tests. *Tribology Letters*, 47(1), 91-102.
- Dharma, S., Masjuki, H. H., Ong, H. C., Sebayang, A. H., Silitonga, A. S., Kusumo, F., and Mahlia, T. M. I. (2016). Optimization of biodiesel production process for mixed *Jatropha curcas*–*Ceiba pentandra* biodiesel using response surface methodology. *Energy Conversion and Management*, 115, 178-190.
- Discenzo, F. M. (2005). System and method for dynamic lubrication adjustment for a lubrication analysis system, Google Patents. US006877360B1
- Dmitri, K. D. (2016). Mechanism of wear. Retrived from [http://www.substech.com/dokuwiki/doku.php?id=mechanisms\\_of\\_wear](http://www.substech.com/dokuwiki/doku.php?id=mechanisms_of_wear)

- Dmochowski, W. M. and Webster, M. N. (2005). The effect of lubricant viscosity-temperature characteristics on the performance of plain journal bearings. *Proceedings of WTC2005*. World Tribology Congress III. National Research Council of Canada and ASME. WTC2005-64229
- Dufresne, A. (2008). Polysaccharide nano crystal reinforced nanocomposites. *Canadian Journal of Chemistry*, 86(6), 484-494.
- Dwivedi, D. K. (2010). Adhesive wear behaviour of cast aluminium–silicon alloys: Overview. *Materials and Design (1980-2015)*, 31(5), 2517-2531.
- Eichhorn, S. J. and Sampson, W. W. (2010). Relationships between specific surface area and pore size in electrospun polymer fibre networks. *Journal Royal Society Interface*. 7(45), 641–649.
- Erdemir, A. (2005). Review of engineered tribological interfaces for improved boundary lubrication. *Tribology International*, 38(3), 249-256.
- Ettefaghi, E., Ahmadi, H., Rashidi, A., Mohtasebi, S. S., and Alaei, M. (2013). Experimental evaluation of engine oil properties containing copper oxide nanoparticles as a nanoadditive. *International Journal of Industrial Chemistry*. 1-6.
- Glidewell, J. and Korcek, S. (1998). Piston ring/cylinder bore friction under flooded and starved lubrication using fresh and aged engine oils, *SAE Technical Paper*. 982659
- Gohar, R., and Rahnejat, H. (2008). *Fundamentals of Tribology* (T. K. Wei Ed.). London: Imperial College Press.
- Gonçalves, D., Vieira, A., Carneiro, A., Campos, A. V., and Seabra, J. H. O. (2017). Film Thickness and Friction Relationship in Grease Lubricated Rough Contacts. *Lubricants*, 25(34).
- Gulzar, M., Masjuki, H. H., Kalam, M. A., Varman, M., Zulkifli, N. W. M., Mufti, R. A. and Zahid, R. (2016). Tribological performance of nanoparticles as lubricating oil additives. *Journal of Nanoparticle Research*, 18(8), 223.

- Haddad, Z., Abid, C., Oztop, H. F., and Mataoui, A. (2014). A review on how the researchers prepare their nanofluids. *International Journal of Thermal Science*, 168-189.
- Harta, I. C., Owens, K., De Jesús Santiago, S. and Schall, D.. (2013). Tribological performance of ZnO-oil nanofluids at elevated temperatures. *SAE International Journal of Fuels and Lubricants*, 6(2013-01-1219), 126-131.
- Hassani, S., Saidu R., Mekhilef, S., and Hepbasli, A. (2015). A new correlation for predicting the thermal conductivity of nanofluids; using dimensional analysis. *International Journal of Heat and Mass Transfer*, 90(2015), 121–130.
- He-long, Y., Yi, X., Pei-jing, S., Bin-shi, X., Xiao-li, W., and Qian, L. (2007). Tribological properties and lubricating mechanisms of Cu nanoparticles in lubricant. *Transactions of nonferrous metals society of China*, 636-642.
- Herrera, M. A., Herrera, A.P. and Mathew, K.O. (2014). Gas permeability and selectivity of cellulose nanocrystals films (layers) deposited by spin coating. *Carbohydrate polymers*, 112, 494-501.
- Hutchings, I. M. (2016). Leonardo da Vinci' s studies of friction. *Wear*, 360, 51-66.
- Hironaka, S. (1984). Boundary lubrication and lubricants. *Three Bond Technical News*. Issued July 1
- Hutchings, I. M. (1992). *Tribology friction and wear of engineering materials*. Cambridge: Butterworth-Heinemann. ISBN: 9780340561843
- Idris, C., Vezir, A., Adnan, P., Omer, S., and Zafer, A. (2014). The effect of different fuels on wear between piston ring and cylinder, *Advances in Mechanical Engineering*, 8.
- Jatti, V. S., and Singh, T. P. (2015). Copper oxide nano-particles as friction-reduction and anti-wear additive in lubricating oil. *Mechanical Science and Technology*, 2, 793-798.
- Jiao, D., Zheng, S., Wang, Y., Guan, R., and Cao, B. (2011). The tribology properties of alumina/silica composite nanoparticles as lubricant additives. *Applied Surface Science*, 257(13), 5720-5725.

- Joly-Pottuz, L., Vacher, B., Ohmae, N., Martin, J. M., and Epicier, T. (2008). Anti-wear and friction reducing mechanisms of carbon nano-onions as lubricant additives. *Tribology Letters*, 30(1), 69-80.
- Jost, H. P. (1966). Lubrication: Tribology; Education and Research; Report on the Present Position and Industry's Needs (submitted to the Department of Education and Science by the Lubrication Engineering and Research) Working Group, HM Stationery Office.
- Juozas, P., Raimundas, R., Igoris, P., and Raimondas, K. (2013). Tribological properties of lubricant additive of Fe,Cu and Co nanoparticle. *Tribology International*, 60(2013), 224–232.
- Kalam, M. A., Masjuki, H. H., Varman, M., and Liaquat, A. M. (2005). Friction and wear characteristics of waste vegetable oil contaminated lubricants. *International Journal of Mechanical and Materials Engineering (IJMME)*, 6(3), 431-436.
- Kapsiz, M., Durat, M., and Ficici, F. (2011). Friction and wear studies between cylinder liner and piston ring pair using Taguchi Method design method. *Advance in Engineering Software*, 595-603.
- Khalilpourazary, S. and S. Meshkat (2014). Investigation of the effects of alumina nanoparticles on spur gear surface roughness and hob tool wear in hobbing process. *The International Journal of Advanced Manufacturing Technology*, 71(9-12), 1599-1610.
- Kökkülünk, G., Parlak, A., Ayhan, V., Cesur, I., Gonca, G., and Boru, B. (2014). Theoretical and experimental investigation of steam injected diesel engine with EGR. *Energy*, 74, 331-339.
- Kovalchenko, A., Ajayi, O., Erdemir, A., Fenske G. and Etsion, I. (2005). The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact. *Tribology International*, 38(3), 219-225.
- Kovarikova, I., Simekova, B., Hodulova, E., and Ulrich, K. (2011). Properties of composite wear resistant layers created by laser beam. *Annals of DAAAM and Proceedings*, 1193-1195.

- Khuri, A. I., and Cornell, J. A. (1996). *Response surfaces: designs and analyses*, (Vol. 152), CRC press.
- Koshy, C. P., Rejendrakumar, P. K., and Thottackad, M. V. (2015). Evaluation of the tribological and thermo-physical properties of coconut oil added with MoS<sub>2</sub> nanoparticle at elevated temperatures. *Wear*, 288-308.
- Kozuch, E., Nomikos, P., Rahmani, R., Morris, N., and Rahnejat, H. (2018). Effect of Shaft Roughness on the Performance of Radial Lip Seals. *Lubricants*, 6(9),1-16.
- Kuo, C. H. (2011). Tribology-Lubricant and Lubrication. InTech
- Laad, M., and Jatti, V. K. S. (2016). Titanium oxide nanoparticles as additives in engine oil. *Journal of King Saud University-Engineering Sciences*, 30(2), 116-122.
- Lancaster, J. K. 1990. A review of the influence of environmental humidity and water on friction, lubrication and wear. *Tribology International*, 25(6), 371-389.
- Lani, N., Ngadi, N., Johari, A., and Jusoh M. (2014). Isolation, characterization, and application of CNC from oil palm empty fruit bunch fiber as nanocomposites. *Journal of Nanomaterials*, 2014(702538), 9.
- Le Goff, K. J., Jouanneau, D., Garnier, C., and Aubry, T. (2014). Gelling of cellulose nanowhiskers in aqueous suspension. *Journal of Applied Polymer Science*, 131(17), 8476-8481.
- Lee, K., Hwang, Y., Cheong, S., Kwon, L., Lee, J. (2009). Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil. *Current Applied Physics*, 9(2), 128-131.
- Leger, C. B. (1992). A Study of Selected Phenomena Observed During Rotary Kiln Incineration. ( Doctoral dissertation, Louisiana State University). Retrieved from [https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=6392&context=grads\\_chool\\_disstheses](https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=6392&context=grads_chool_disstheses)
- Li, W-C., An-Hui Lu, A-H., Weidenthaler, C., Goddard, R., Bongard, H-j., and Schu"th, F. (2005). Growth of single crystal  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> nanofibers on a carbon aerogel substrate. *Journal of Materials Chemistry*, 15, 2993–2996.

- Li, W., Zheng, S., Cao, B., and Ma, S. (2011). Friction and wear properties of ZrO<sub>2</sub>/SiO<sub>2</sub> composite nanoparticles. *Journal of Nanoparticle Research*, 13(5), 2129-2137.
- Livo Lubricants (2013) (online). Retrived from <http://www.livo.us/engineoilform.html>
- Luksa, A. (1990). Viscosity properties of base lubricating oils containing mineral oil, synthetic ester oil and polymeric additives. *Lubrication Science*, 7(3), 187-192.
- Scott, R. (2016). Basic wear modes in lubricated systems. Retrieved from <https://www.machinerylubrication.com/Read/1375/wear-modes-lubricated>.
- Luo, T., Wei, X., Huang, X., Huang, L., and Yang, F. (2014). Tribological properties of Al<sub>2</sub>O<sub>3</sub> nanoparticles as lubricating oil additives. *Ceramics International*, 40(5), 7143-7149.
- Maru, M. M., and Tanaka, D. K. (2006). Influence of Loading, Contamination and Additive on the Wear of a Metallic Pair under Rotating and Reciprocating Lubricated Sliding. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, XXVIII(3), 278-285
- McCoy, S. (2007). *The development of an engine lubricant containing soybean oil*. (Master's thesis, University of Kentucky UKnowledge) Retrieved from [https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1500&context=gradschool\\_theses](https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1500&context=gradschool_theses)
- Merlo, A. M. (2003). The contribution of surface engineering to the product performance in the automotive industry. *Surface and Coatings Technology*, 174, 21-26.
- Milojević S., Pešić R., and Taranović, D. (2015). Tribological Principles of Constructing the Reciprocating Machines. *Tribology in Industry*, 37(1), 13-19.
- Minami, I, and Sugibuchi, A. (2012). Surface Chemistry of Aluminium Alloy Slid against Steel Lubricated by Organic Friction Modifier in Hydrocarbon Oil. *Advances in Tribology*, 2012 (926870), 7 pages.
- Mishra, P. C. (2013). Modeling for Friction of Four Stroke Four Cylinder In-Line Petrol Engine. *Tribology in Industry*, 35(3), 237-243.

- Mobarak, H. M., Niza Mohamad, E., Masjuki, H. H., Kalam, M. A., Al Mahmud, K. A. H., Habibullah, M., and Ashraful, A. M. (2014). The prospects of biolubricants as alternatives in automotive applications. *Renewable and Sustainable Energy Reviews*, 33(2014), 34-43.
- Mohammad, M. (2017). The Effect of Thermal Conductivity Enhancement for Brownian motion of Nanofluids. *International Journal of Nanotechnology and Applications*, 11(1), 109-116.
- Morris, N. J., Rahmani, R. and Rahnejat, H., (2017). A hydrodynamic flow analysis for optimal positioning of surface textures. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 231(9),1140-1150.
- Murshed, S., Leong K., and Yang C. (2008). Investigations of thermal conductivity and viscosity of nanofluids. *International Journal of Thermal Sciences*, 47(5), 560-568.
- Murthy, H. and Vadivuchezhian, K. (2017). Estimation of friction distribution in partial-slip contacts from reciprocating full-sliding tests. *Tribology International*, 108: 164-173.
- Nagulkar, N. S. and S. Lawankar (2017). Study of Properties of Nanofluids and its Effect. *International Research Journal of Engineering and Technology*, 04(06), 2584-2588.
- Nehme, G. (2015). Toward the minimization of friction and wear using fluorinated additive under extreme boundary lubrication in fully formulated oil. *Journal of Energy and Economic Development*, 1(1), 10-21.
- Nine, M. J., Batmunkh, M., Kim, J.-H., Chung, H.-S., and Jeong, H.-M. (2012). Investigation of Al<sub>2</sub>O<sub>3</sub>-MWCNTs hybrid dispersion in water and their thermal characterization, *Journal Nanoscience Nanotechnology*, 12(6), 4553–4559.
- Padgurskas, J., Rukuiza, R., Prosyčėvas, I., and Kreivaitis, R. (2013). Tribological properties of lubricant additives of Fe, Cu and Co nanoparticles, *Tribology International*, 60(2013), 224-232.



- Parsian, A., and Akbari, M. (2018). New experimental correlation for the thermal conductivity of ethylene glycol containing Al<sub>2</sub>O<sub>3</sub>-Cu hybrid nanoparticles, *Journal of Thermal Analysis and Calorimetry*, 131(2), 1605-1613.
- Peña-Parás, L., Taha-Tijerina, J., Garza, L., Maldonado-Cortés, D., Michalczewski, R., and Lapray, C. (2015). Effect of CuO and Al<sub>2</sub>O<sub>3</sub> nanoparticle additives on the tribological behavior of fully formulated oils. *Wear*, 332-333, 1256-1261.
- Peng, D. X., Chen, C. H., Kang, Y., Chang, Y. P., and Chang, S. Y. (2010). Size effects of SiO<sub>2</sub> nanoparticles as oil additives on tribology of lubricant. *Industrial Lubrication and Tribology*, 62(2), 111-120.
- Peng, D. X., Kang, Y., Chen, S., Shu, F., and Chang, Y. (2010). Dispersion and tribological properties of liquid paraffin with added aluminum nanoparticles. *Industrial Lubrication and Tribology*, 62(6), 341-348.
- Peric, S., Nedic, B., Trifkovic, D., and Vuruna, M. (2013). An experimental study of the tribological characteristics of engine and gear transmission oils. *Journal of Mechanical Engineering*, 59(7-8), 443-450.
- Piriyawong, V., Thongpool, V., Asanithi, P., and Limsuwan, P. (2012). Preparation and Characterization of Alumina Nanoparticles in Deionized Water Using Laser Ablation Technique. *Journal of Nanomaterials*, 2012( 819403), 6 pages.
- Pitthili, H. (2014). *Tribology in Engineering* (2014 ed.). Croatia: InTech.
- Qiu, S., Zhou, Z., Dong, J., and Chen, G. (2001). Preparation of Ni nanoparticles and evaluation of their tribological performance as potential additives in oils. *Journal of Tribology*, 123(3), 441-443.
- Rabaso, P., Ville, F., Dassenoy, F., Diaby, M., Afanasiev, P., Cavoret, J., Vacher, B., Le Mogne, T. (2014). Boundary lubrication: influence of the size and structure of inorganic fullerene-like MoS<sub>2</sub> nanoparticles on friction and wear reduction. *Wear*, 320, 161-178.
- Rahman, M.M., Kadirgama, K., and Azma Salwani Ab Aziz, A. S. (2014). Artificial neural network modeling of grinding of ductile cast iron using water based SiO<sub>2</sub> nanocoolant. *International Journal of Automotive and Mechanical Engineering (IJAME)*, 9, 1649-1661.

- Raj, D. A., and Senthivelan, T. (2015). Empirical modelling and optimization of process parameters of machining titanium alloy ny wire-EDM using RSM. *materialtoday:proceeding*, 2(4-5), 1682-1690.
- Ran, X., Yu, X., and Zou, Q. (2016). Effect of Particle Concentration on Tribological Properties of ZnO Nanofluids. *Tribology Transactions*, 60(1), 154-158.
- Richardson, D. E. (2000). Review of power cylinder friction for diesel engines. *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, 122(4), 506-519.
- Rob H., (2012). *Lubricant Additives*. STLE Houston, R.T. Vanderbilt Company. Inc.
- Rohr W. F. (2013). *Experimental and Theoretical Investigations of Lube Oil Perg=formenace and Engine Friction*. (Doctoral Dissertations, University of Tennessee, Knoxville) Retrieved from [https://trace.tennessee.edu/cgi/viewcontent.cgi?referer=http://trace.tennessee.edu/cgi/viewcontent.cgi?article=2828&context=utk\\_graddiss&httpsredir=1&article=2828&context=utk\\_graddiss](https://trace.tennessee.edu/cgi/viewcontent.cgi?referer=http://trace.tennessee.edu/cgi/viewcontent.cgi?article=2828&context=utk_graddiss&httpsredir=1&article=2828&context=utk_graddiss)
- Roomi, Y., Hussein, K. F., and Riazi, M. R. (2012). Inhibition efficiencies of synthesized anhydride based polymers as scale control additives in petroleum production. *Journal of Petroleum Science and Engineering*, 81, 151-160.
- Sadaka, S., and Boateng, A. A. (2009). Pyrolysis and bio-oil. Agriculture and Natural Resources. Retrieved from <https://www.uaex.edu/publications/PDF/FSA-1052.pdf>
- Sacui, I. A., Nieuwendaal, R. C., Burnett, D. J., Stranick, S. J., Jorfi, M., Weder, C., Foster, E. J., Olsson, R. T., and Gilman, J. W. (2014). Comparison of the Properties of Cellulose Nanocrystals and Cellulose Nanofibrils Isolated from Bacteria, Tunicate, and Wood Processed Using Acid, Enzymatic, Mechanical, and Oxidative Methods. *ACS Applied Materials Interfaces*, 6(9), 6129–6138.
- Sajid, M. U., and Ali, H. M. (2018). Thermal conductivity of hybrid nanofluids: A critical review. *International Journal of Heat and Mass Transfer*, 126, 211-234.

- Sakinah H, Kadirgama, K., Ramasamy, D., Noor, M. M., Amirruddin, A. K., Najafi, G., Rahman, M. M. (2017). Waste Cooking Oil Blended with the Engine Oil for Reduction of Friction and Wear on Piston Skirt. *Fuel*, 205(2017), 247-261.
- Sharif, M., Azmi, W. H., Redhwan, A. A. M., Mamat, R. (2016). Investigation of thermal conductivity and viscosity of Al<sub>2</sub>O<sub>3</sub>/PAG nanolubricant for application in automotive air conditioning system. *International journal of Refrigeration*, 70, 93-102.
- Sharma, M. D., Sehgal, R., and Pant, M. (2016). Modeling and optimization of friction and wear characteristics of Ti<sub>3</sub>Al<sub>2</sub>.5V Alloy under dry sliding condition. *Journal of Tribology*, 138, 1-18.
- Shivaprakash, Y.M., Gowrishankar, M.C., Sharma, S.S., and Sreenivasa Prasad, V. (2016). Experimental Studies On Grey Cast Iron Reinforced Aa6061 Composite. *International Journal of Mechanical And Production Engineering*, 4(3).
- Shiyu, M., Shaohua, Z., Cao, D., and Guo, H. (2010). Anti-wear and friction performance of ZrO<sub>2</sub> nanoparticles as lubricant additive. *Particuology*, 8(5), 468-472.
- Singh, A. (2008). Thermal conductivity of nanofluids. *Defence Science Journal*, 58(5), 600-607.
- Spikes, H. (2015). Friction Modifier Additives. *Tribology Letters*, 60(1), 1-26.
- Srivastava, S. P. (2009). Developments in Lubricant Technology. John Wiley & Son
- Stachowiak, G. and A. W. Batchelor (2013). Engineering tribology, Butterworth-Heinemann.
- Suresh, S., Venkitaraj, K. .P., Selvakumar, P., and Chandrasekar, M. (2011). Synthesis of Al<sub>2</sub>O<sub>3</sub>-Cu/water hybrid nanofluids using two step method and its thermos physical properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 388(1-3), 41-48.
- Syaima, M. T. S., Zamratul, M. I. M., Noor, I. M., Rifdi, and W.M.W.T. (2014). Development of bio-lubricant from Jatropha curcas oils. *Int'l Journal of Research in Chemical, Metallurgical and Civil Engineering*, 1(1), 1442-1450.

- Tahat, M. S. and Benim, A.C. (2017). Experimental analysis on thermophysical properties of Al<sub>2</sub>O<sub>3</sub>/CuO hybrid nano fluid with its effects on flat plate solar collector. *Defect and Diffusion Forum*, 374, 148–156.
- Taniguchi, T. and Okamura, K. (1998). New films produced from microfibrillated natural fibres. *Polymer International*, 47(3), 291-294.
- Takamori, S., Osawa Y., and Halada, K. (2002). Aluminium-Alloyed Cast Iron as a Versatile Alloy. *Materials Transactions*, 43(3), 311-314.
- Tao, H., Dong, Z., Jiayu, W., and Jane, W. Q. (2016). Experimental and numerical investigations of the Stribeck curve for lubricated counterformal contacts. *Journal of Tribology*, 139(2), 13.
- Tekindal, M. A., Bayrak, H., Ozkaya, B., and Genc, Y. (2012). Box-Behnken experimental design in factorial experiment: the importance of bread for nutrition and health. *Turkish Journal of Field Crops*, 17(2), 115-123.
- Theo, M., Kirsten, B., and Thorsten, B. (2011). *Industrial Tribology*. Germany: Wiley-VCH Verlag and Co.KGaA. ISBN:9783527320578
- Thottackkad, M. V., Perikinalil, R. K., and Kumarapillai, P. N. (2012). Experimental evaluation on the tribological properties of coconut oil by the addition of CuO nanoparticles. *International Journal of Precision Engineering and Manufacturing*, 13(1), 111-116.
- Tung, S. C., and McMillan, M. L. (2004). Automotive tribology overview of current advances and challenges for the future. *Tribology International*, 37(7), 517-536.
- Unal, O. (2016). Optimization of shot peening parameters by response surface methodology. *Surface and Coatings Technology*, 305, 99-109.
- Uetani K. and Hatori K. (2017). Thermal conductivity analysis and applications of nanocellulose materials. *Science Technology Advance Materials*, 18(1), 877-892.
- Velu, S., Kapoor, M., Osaki, T., Suzuki, K., and Ohashi, F. (2001). Oxidative Steam Reforming of Methanol over CuZnAl(Zr)-Oxide Catalysts for the Selective Production of Hydrogen for Fuel Cells. *Applied Catalysis A: General*, 213(1), 47-63.

- Viesca, J. L., Battez, A. H., González, R., Chou, R., and Cabello, J. J. (2011). Antiwear properties of carbon-coated copper nanoparticles used as an additive to a polyalphaolefin. *Tribology International*, 44(7–8), 829-833.
- Vishweshwara, S. C., and Badi, O. K. H. A. (2015). Density and thermal conductivity changes in engine oil during its life cycle: An experimental study. *Multidisciplinary Science and Engineering*, 6, 24-28.
- John, W. (1994). *Engineering Tribology*. New York: Oxford University Press.
- Wang, N., and Komvopoulos, K. (2010). Nanomechanical and friction properties of ultrathin amorphous carbon films studied by molecular dynamics analysis. *STLE/ASME 2010 International Joint Tribology Conference*. American Society of Mechanical Engineers. IJTC2010-41222, 393-395.
- Wei, B., Zou, C., Yuan, X., and Li, X. (2017). Thermo-physical property evaluation of diathermic oil based hybrid nanofluids for heat transfer applications. *Int. J. Heat Mass Transfer*, 107, 281–287.
- Wen D., Lin G., Vafaei S., and Zhang K. (2009). Review of nanofluids for heat transfer applications. *Particuology*, 7(2), 141-150.
- Wu, X., Chabot, V. L., Kim, B. K., Yu, A., Berry, R. M., and Tam, K. C (2014). Cost-effective and scalable chemical synthesis of conductive cellulose nanocrystals for high-performance supercapacitors. *Electrochimica Acta*, 138, 139-147.
- Wu, Y. Y., Tsui, W. C., and Liu, T. C. (2007). Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. *Wear*, 262(7-8), 819-825.
- Xie, H., Jiang, B., He, J., Xia, X., and Pan, F. (2015). Lubrication performance of MoS<sub>2</sub> and SiO<sub>2</sub> nanoparticles as lubricant additives in magnesium alloy-steel contacts. *Tribology International*, 93(A), 63-70.
- Xu., X., Liu, F., Jiang, L., Zhu, J. Y., Haagenson, D., and Wiesenborn, D. P. (2013). Cellulose Nanocrystals vs. Cellulose Nanofibrils: A Comparative Study on Their Microstructures and Effects as Polymer Reinforcing Agents. *ACS Applied Materials & Interfaces*, 5(8), 2999–3009.

- Yan, M., Zhang M, Dong F., Li S., Li C., and Li W. (2013). Characterization of surface acetylated nanocrystalline cellulose by single-step method. *BioResources*, 8(4), 6330-6341.
- Yu, W., Xie, H., Li, Y. (2009). Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid. *Thermochimica Acta*, 491(1-2), 92-96.
- Zhang, Z. J., Simionesie, D., and Schaschke, C. (2014). Graphite and hybrid nanomaterials as lubricant additive. *Lubricants*, 2, 44-65.
- Zhou, J., Wu, Z., Zhang, Z., Liu, W., and Xue, Q. (2000). Tribological behavior and lubricating mechanism of Cu nanoparticles in oil. *Tribology Letters*, 8(4), 213-218.
- Zhu, H., Jia, Z., Chen, Y., Weadock, N., Wan, J., Vaaland, O., Han, X., Li, T., and Hu, L. (2013). Tin anode for sodium-ion batteries using natural wood fiber as a mechanical buffer and electrolyte reservoir. *Nano Lett*, 13(7), 3093–3100.
- Zulkifli, N. W. M., Kalam, M.A., Masjuki, H. H. and Yunus, R. (2013). Experimental analysis of tribological properties of chemically modified bio-based lubricant with nanoparticle additives. *Procedia Engineering*, 68(2013), 152-157.