TRIBOLOGICAL BEHAVIOR OF WASTE COOKING OIL BLENDED LUBRICANT

SAKINAH MUHAMAD HISHAM

MASTER OF ENGINEERING (MECHANICAL)

UNIVERSITI MALAYSIA PAHANG

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 Master of Engineering (Mechanical).

_____

(Supervisor's Signature)

Full Name :

Position :

Date :

_____

(Co-supervisor's Signature)

Full Name :

Position :

Date :

STUDENT'S DECLARATION

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.

_____

(Student's Signature)

Full Name : SAKINAH MUHAMAD HISHAM

ID Number : MMM14027

Date : 20 JAN 2017

TRIBOLOGICAL BEHAVIOR OF WASTE COOKING OIL BLENDED LUBRICANT

SAKINAH MUHAMAD HISHAM

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Engineering

Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

JANUARY 2017

ACKNOWLEDGEMENTS

By the name of Allah, the most Gracious, the Most Merciful. Praise be to Allah, the Lord of the World; peace and blessings of Allah be upon the noblest of the Prophets and Messengers, our Prophet MOHAMMED and his family, companions and who follows him until the last day.

First and foremost I wish to thank my advisor, Dr Devarajan for his support since the days I began working on my research. Also, I would like to thank my co-supervisor, Assoc. Prof. Dr. Kumaran Kadirgama for his support my research by science and financial.

Next, I would like to thank the Faculty of Mechanical Engineering and all staff. The staff of the thermal laboratory in Mechanical Faculty deserves great my appreciated. Thanks also, for all my friends (students in Universiti Malaysia Pahang) to help me during the working. Thank you very much to all my brothers and friends for their concern.

Last but not least, the moral support from my family and consideration from the beginning of my postgraduate life is a large piece of motivation

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

μ	Coefficient of friction
VI	Viscosity index
F	Force
F_f	Friction force
N	Load
f	Friction factor
F	Force
f_s	Skin friction coefficient
g	Gravity

LIST OF ABBREVIATIONS

WCO	Waste cooking oil
DOE	Design of experiment
COF	Coefficient of friction
WR	Wear rate
WVO	Waste vegetable oil
FFA	Free fatty acid
RSM	Response surface methodology
EDX	Energy dispersive X-spectroscopy
ANOVA	Analysis of variance
DF	Diesel fuel
PB	Palm biodiesel
JB	Jathropa biodiesel
TMP	Trimethylolpropane
POD	Palm oil diesel
CCD	Composite rotatable design
SV	Sliding velocity
NF	Normal force
MOOT	Multi objectives optimization
RF	Reinforcement

TRIBOLOGICAL BEHAVIOR OF WASTE COOKING OIL BLENDED LUBRICANT

SAKINAH MUHAMAD HISHAM

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Engineering

Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

JANUARY 2017

ABSTRAK

Dalam dekad semasa, pembangunan produk yang boleh di kitar semula untuk menggantikan produk fosil adalah satu isu yang penting terutama dari industri, alam sekitar dan dari sudut pandangan ahli akademik. Dalam tesis ini, percubaan telah dibuat untuk mengkaji ciri-ciri tribologi minyak masak terpakai yang dicampur dengan minyak enjin SAE 40, menyiasat ciri-ciri fizikal minyak seperti kelikatan dan kandungan kelembapan dan mengkaji tentang pengaruh parameter operasi yang berbeza dalam prestasi tribologi. Minyak masak kelapa sawit terpakai telah dipilih disebabkan ia adalah minyak yang biasa dipakai di Malaysia. Minyak masak terpakai telah melalui tiga proses penapisan, penapisan kasar, penyahairan dan penapisan halus. Kelembapan kandungan minyak dan analisa kelikatan telah dikaji untuk mengetahui ciri-ciri fizikal minyak pelincir yang telah dicampur. Mekanisme haus dan prestasi geseran telah dinilai menggunakan satu mesin yang menyerupai aplikasi seperti geseran antara piston dan liner silinder di dalam enjin. Bahan spesimen yang digunakan untuk specimen adalah aluminum 6061 yang merupakan bahan biasa digunakan dalam pembuatan piston. Cabang reka bentuk eksperimen (DOE) iaitu kaedah gerak balas permukaan (RSM) telah digunakan untuk mengkaji tentang pengaruh parameter operasi yang berbeza seperti kelajuan putaran (200 RPM, 250 RPM, 300 RPM), kepekatan jumlah (5% dan 10% daripada sisa minyak), dan beban (2 kg, 5.5 kg dan 9kg) dalam menentukan dan mendapatkan pengoptimuman untuk pelincir yang berbeza dalam aspek tribology. Field Pelepasan Mikroskop Imbasan Elektron (FESEM) yang dilengkapi dengan EDX sistem telah digunakan untuk mengenal pasti mekanisme haus dan untuk mengesan semua kecacatan yang mungkin berlaku pada permukaan specimen. Hasil eksperimen menunjukkan bahawa mengikut pekali geseran berbanding hasil masa dan hasil penurunan berat spesimen, pekali geseran antara tiga kepekatan minyak tidak menunjukkan perbezaan yang besar. Berdasarkan keputusan kandungan lembapan dalam minyak yang telah dicampur, keputusan menunjukkan bahawa kandungan lembapan dalam 0% kepekatan jumlah sisa minyak masak adalah sama dengan kandungan lembapan peratusan dalam 10% kepekatan jumlah sisa minyak masak manakala 5% menunjukkan peratusan yang paling rendah kandungan lembapan manakala berdasarkan keputusan kelikatan minyak, semakin tinggi kandungan minyak masak yang dicampur, semakin kurang kadar kelikatan minyak. Berdasarkan keputusan FESEM, didapati bahawa penurunan mekanisma haus berlaku apabila menggunakan minyak yg lebih likat. Ini kerana minyak yang likat akan mengurangkan daya geseran antara dua bahan yang bergesel. Merujuk di barisan mengasah di atas spesimen , ia tidak menunjukkan perbezaan yang besar di antara spesimen yang berbeza. Ini menunjukkan bahawa menggunakan sedikit minyak masak terpakai tidak memberi banyak kesan dalam komponen enjin dari segi pekali mereka geseran dan mekanisme haus. Untuk ciri-ciri fizikal minyak peliincir pula, keputusan menunjukkan minyak pelincir yang telah dicampur minyak masak terpakai menghampiri dengan minyak enjin yang sedia ada iaitu SAE 40.

ABSTRACT

In the current decade, the development of renewable products to replace fossil products is an essential and important issue from industrial, environment, and academic point of views. In the current study, an attempt was made to study the tribological behaviour of waste cooking oil blended with SAE 40, investigate their viscosity and moisture content and also optimized the differemt operating parameter of the tribological performance. Waste cooking palm oil (WCO) was chosen from the most common waste oil using in Malaysia. Waste cooking oil was undergone three types of process, the coarse filtering, dewatering and fine filtering. Moisture content and viscosity analysis were investigated to study the physical properties of blended lubricant as well as the effectiveness of filtration method. Wear and friction performance was evaluated using piston-liner contact tester, and the material use is aluminium 6061 which is the standard material for piston. The design of experiment (DOE) was constructed using Response Surface Methodology (RSM) method. Influence of different operating parameter such as rotational speeds (200 RPM,250 RPM, 300 RPM), volume concentration (SAE 40, 5% and 10% of waste oil), and applied loads (2 kg, 5.5kg and 9kg) investigated and obtain the optimization for different lubricant in tribological behavior. Field Emission Scanning Electron Microscope (FESEM) that equipped with EDX system was used to identify the wear mechanism and element on the surface of the specimen. According to the coefficient of friction versus time result and the weight loss result, the friction coefficient between the three concentrations of oil shows a considerable difference between SAE 40 and two blended lubricant. Based on the properties result, for viscosity, as the concentration of waste cooking oil increases, the viscosity of the bio-lubricant decreases. According to result in moisture content, the moisture content percentage in 0% volume concentration of waste cooking oil is the same with moisture content percentage in 10% volume concentration of waste cooking oil while 5% shows the lowest percentage of the moisture content. Based on SEM result, the wear on the surface specimen decrease as the concentration of waste cooking oil added with engine oil reduce, and it was due to the SAE 40 showed the highest viscosity result compared to 10% concentration because higher viscosity tends to drag the movements between two contact surfaces. It can be said that using a small amount of WCO in the engine oil was not give much impact in the engine component regarding on their coefficient of friction and wear mechanism. From the lubricant properties analysis, it shows that the properties of the blended lubricant approached with the lubricant baseline (SAE 40).

REFERENCES

Adhvaryu, A., Liu, Z., & Erhan, S. Z. (2005). Synthesis of novel alkoxylated triacylglycerols and their lubricant base oil properties. *Industrial Crops and Products, 21*(1), 113-119

Agarwal, G., Patnaik, A., & Sharma, R. K. (2012). Parametric optimization of three-body abrasive wear behavior of bidirectional and short kevlar fiber reinforced epoxy composites.

Amoser, M., Demmerle, R., Barrow, S., Terrettaz, F., & Jaquet, D. (2001). Insights into piston-running behaviour. *Marine News*(2-2001)

Andersson, B. S. (1991). Paper XVIII (iii) Company Perspectives in Vehicle Tribology - Volvo. In C. M. T. D. Dowson & M. Godet (Eds.), *Tribology Series* (Vol. Volume 18, pp. 503-506): Elsevier.

Andersson, P. (2003). A new tribometer for piston ring friction measurements. *Tribology Series, 41*, 501-510

Andersson, P., Tamminen, J., & Sandström, C.-E. (2002). Piston ring tribology. *A literature survey. VTT Tiedotteita-Research Notes, 2178*(1)

Arumugam, S., & Sriram, G. (2012). Effect of Bio-Lubricant and Biodiesel-Contaminated Lubricant on Tribological Behavior of Cylinder Liner–Piston Ring Combination. *Tribology Transactions, 55*(4), 438-445

Arumugam, S., Sriram, G., & Ellappan, R. (2014). Bio-lubricant-biodiesel combination of rapeseed oil: An experimental investigation on engine oil tribology, performance, and emissions of variable compression engine. *Energy, 72*, 618-627

Asadauskas, S., Perez, J. H., & Duda, J. L. (1997). Lubrication properties of castor oil--potential basestock for biodegradable lubricants. *Tribology & Lubrication Technology, 53*(12), 35

Aue, G. (1975). *Piston ring scuffing-General review*. Paper presented at the Proceeding of Conference Sponsored by the Tribology Group, the Combustion Engines Group, and the Automobile Division of the Institution of Mechanical Engineers.

Balasubramaniam, B., Sudalaiyadum Perumal, A., Jayaraman, J., Mani, J., & Ramanujam, P. (2012). Comparative analysis for the production of fatty acid alkyl esterase using whole cell biocatalyst and purified enzyme from Rhizopus oryzae on waste cooking oil (sunflower oil). *Waste Management, 32*(8), 1539-1547

Barnes, A. M., Bartle, K. D., & Thibon, V. R. A. (2001). A review of zinc dialkyldithiophosphates (ZDDPS): characterisation and role in the lubricating oil. *Tribology International, 34*(6), 389-395

Bell, J. C. (1993). Engine lubricants. In C. M. Taylor (Ed.), *Tribology Series* (Vol. Volume 26, pp. 287-301): Elsevier.

Bezerra, M. A., Santelli, R. E., Oliveira, E. P., Villar, L. S., & Escaleira, L. A. (2008). Response surface methodology (RSM) as a tool for optimization in analytical chemistry. *Talanta, 76*(5), 965-977

Bhale, P. V., Deshpande, N., & Thombre, S. (2008). Simulation of wear characteristics of cylinder liner ring combination with diesel and biodiesel. *Society of Automotive Engineers*

Bijwe, J., Garg, A., & Gandhi, O. (2000). Reassessment of engine oil periodicity in commercial vehicles. *Tribology & Lubrication Technology, 56*(1), 23

Çakir, M., & Akçay, I. H. (2014). Frictional behavior between piston ring and cylinder liner in engine condition with application of reciprocating test. *International Journal of Materials Engineering and Technology, 11*(1), 57

Cesur, İ., Ayhan, V., Parlak, A., Savaş, Ö., & Aydin, Z. (2014). The Effects of Different Fuels on Wear between Piston Ring and Cylinder. *Advances in Mechanical Engineering, 2014*, 1-8

Chambers, K., Arneson, M., & Waggoner, C. (1988). An on-line ferromagnetic wear debris sensor for machinery condition monitoring and failure detection. *Wear, 128*(3), 325-337

Chang, B. P., Akil, H. M., Affendy, M. G., Khan, A., & Nasir, R. B. M. (2014). Comparative study of wear performance of particulate and fiber-reinforced nano-ZnO/ultra-high molecular weight polyethylene hybrid composites using response surface methodology. *Materials & Design, 63*(0), 805-819

Chauhan, P. S., & Chhibber, D. (2013). Non-edible oil as a source of bio-lubricant for industrial applications: a review. *Int J Eng Sci Innov Technol (IJESIT), 2*

Cheenkachorn, K., & Fungtammasan, B. (2010). Development of engine oil using palm oil as a base stock for four-stroke engines. *Energy, 35*(6), 2552-2556

Coy, R. (1998). Practical applications of lubrication models in engines. *Tribology International, 31*(10), 563-571

Dong, J., Van de Voort, F. R., Ismail, A. A., Akochi-Koble, E., & Pinchuk, D. (2000). Rapid determination of the carboxylic acid contribution to the total acid number of

lubricants by Fourier transform infrared spectroscopy. *Lubrication engineering, 56*(6), 12-20

Dong, W., Davis, E., Butler, D., & Stout, K. (1995). Topographic features of cylinder liners—an application of three-dimensional characterization techniques. *Tribology International, 28*(7), 453-463

Dowson, D. (1998). *History of Tribology*: Wiley.

Dufrane, K., & Kannel, J. (1989). Thermally induced seizures of journal bearings. *Journal of tribology, 111*(2), 288-292

Fazal, M. A., Haseeb, A. S. M. A., & Masjuki, H. H. (2011). Effect of temperature on the corrosion behavior of mild steel upon exposure to palm biodiesel. *Energy, 36*(5), 3328-3334

Fazal, M. A., Haseeb, A. S. M. A., & Masjuki, H. H. (2012). Degradation of automotive materials in palm biodiesel. *Energy, 40*(1), 76-83

Fitch, J. C., & Troyer, D. D. (2000). Sampling methods for used oil analysis. *Tribology & Lubrication Technology*, *56*(3), 40

Fujita, E. M., Campbell, D. E., & Zielinska, B. (2006). Chemical analysis of lubrication oil samples from a study to characterize exhaust emissions from light-duty gasoline vehicles in the Kansas City Metropolitan Area. *Final Report*

G.E.P. Box, D. W. B. (1960). *Technometrics 2*.

Glaeser, W. (1992). *Materials for tribology* (Vol. 20): Elsevier.

Glidewell, J., & Korcek, S. (1998). Piston ring/cylinder bore friction under flooded and starved lubrication using fresh and aged engine oils: SAE Technical Paper.

Golloch, R., Kessen, U., & Merker, G. P. (2002). Tribological investigations on the piston assembly group of a diesel engine. *MTZ worldwide, 63*(6), 21-24

Gryglewicz, S., Stankiewicz, M., Oko, F. A., & Surawska, I. (2006). Esters of dicarboxylic acids as additives for lubricating oils. *Tribology International, 39*(6), 560-564

Gulzar, M., Masjuki, H. H., Varman, M., Kalam, M. A., Zulkifli, N. W. M., Mufti, R. A., . . . Arslan, A. (2016). Effects of biodiesel blends on lubricating oil degradation and piston assembly energy losses. *Energy, 111*, 713-721

Gupta, P. (2001). On a multi-process wear model. *LUBRICATION ENGINEERING-ILLINOIS-, 57*(4), 19-24

Haseeb, A. S. M. A., Sia, S. Y., Fazal, M. A., & Masjuki, H. H. (2010). Effect of temperature on tribological properties of palm biodiesel. *Energy, 35*(3), 1460-1464

Haselkorn, M., & Kelley, F. (1992). *Development of Wear Resistant Ceramic Coatings for Diesel Engines.* Paper presented at the SAE CONFERENCE PROCEEDINGS P.

Hatamake, T., Wakuri, Y., Soejima, M., & Kithara, T. (2001). *Some studies on the tribology of diesel engines.* Paper presented at the 23rd CIMAC world congress on combustion engine technology for ship propulsion, power generation, rail traction.

Henein, N. A., Ma, Z., Huang, S., Bryzik, W., & Glidewell, J. (1998). In situ wear measuring technique in engine cylinders. *Tribology Transactions, 41*(4), 579-585

Howard E. Boyer and Timothy L. Gall, E. (1985). *Metals Handbook*. Materials Park, OH: American Society for Metals.

Huang, C., Zong, M.-h., Wu, H., & Liu, Q.-p. (2009). Microbial oil production from rice straw hydrolysate by Trichosporon fermentans. *Bioresource Technology, 100*(19), 4535-4538

Hunt, T. M. (1993). *Handbook of wear debris analysis and particle detection in liquids*: Springer Science & Business Media.

Iijima, T., & Inada, Y. (2001). Piston for internal combustion engines: Google Patents.

Jayadas, N. H., Prabhakaran Nair, K., & G, A. (2007). Tribological evaluation of coconut oil as an environment-friendly lubricant. *Tribology International, 40*(2), 350-354

Johansson, S., Nilsson, P. H., Ohlsson, R., & Rosén, B.-G. (2011). Experimental friction evaluation of cylinder liner/piston ring contact. *Wear, 271*(3), 625-633

John M. (Tim) Holt, T. E. C. Y. H., Ed., . (1996). *Structural Alloys Handbook.* West Lafayette, IN: CINDAS/Purdue University.

Kadirgama, K., & Abou-El-Hossein, K. A. (2005). Power Prediction Model for Milling 618 Stainless Steel Using Response Surface Methodology *American Journal of Applied Sciences, 7*, 1182-1187

Kalam, M. A., Masjuki, H. H., Varman, M., & 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

Kapoor, A., Tung, S. C., Schwartz, S. E., Priest, M., & Dwyer-Joyce, R. S. (2001). Automotive tribology. *Modern Tribology Handbook, 2*, 1187-1229

Kauzlarich, J., & Williams, J. (2001). Archard wear and component geometry. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 215*(4), 387-403

Khuri, A. I., & Cornell, J. A. (1996). *Response surfaces: designs and analyses* (Vol. 152): CRC press.

Koshy, C. P., Rajendrakumar, P. K., & Thottackkad, M. V. (2015). Evaluation of the tribological and thermo-physical properties of coconut oil added with MoS2 nanoparticles at elevated temperatures. *Wear, 330-331*, 288-308

Lacey, P., & Stockwell, R. (1999). Development of a Methodology to Predict Cylinder Liner Scuffing in the 6V92TA Engine Lubricant Test©. *Tribology Transactions, 42*(1), 192-201

Lajis, M. A., KARIM, A. N. M., AMIN, A. K. M. N., HAFIZ, A. M. K., & Turnad, L. G. (2008). Prediction of Tool Life in End Milling of Hardened Steel AISI D2. *European journal of scientific research, vol.4*, pp.592 – 602

Lee, J., & Mudawar, I. (2007). Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels. *International Journal of Heat and Mass Transfer, 50*(3), 452-463

Lipp, S., & Schmidt, R. (2001). *The New FERROCOMP-Piston for High Cylinder Output.* Paper presented at the The 23rd CIMAC Congress in Hamburg.

Ludema, K. C. (1984). A review of scuffing and running-in of lubricated surfaces, with asperities and oxides in perspective. *Wear, 100*(1), 315-331

Ma, Z., Henein, N. A., Bryzik, W., & Glidewell, J. (1998). Break-in liner wear and piston ring assembly friction in a spark-ignited engine. *Tribology Transactions, 41*(4), 497-504

Maleque, M., Masjuki, H., & Ishak, M. (1998). Bio-fuel-contaminated lubricant and hardening effects on the friction and wear of AISI 1045 steel. *Tribology Transactions, 41*(1), 155-159

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

Masjuki, H., & Maleque, M. (1997). Investigation of the anti-wear characteristics of palm oil methyl ester using a four-ball tribometer test. *Wear, 206*(1), 179-186

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*(1–2), 293-299

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

Mehta, D. S., Masood, S. H., & Song, W. Q. (2004). Investigation of wear properties of magnesium and aluminum alloys for automotive applications. *Journal of Materials Processing Technology, 155–156*, 1526-1531

Meurant, G. (2009). *Tribology: a systems approach to the science and technology of friction, lubrication, and wear* (Vol. 1): Elsevier.

Mobarak, H. M., Niza Mohamad, E., Masjuki, H. H., Kalam, M. A., Al Mahmud, K. A. H., Habibullah, M., & Ashraful, A. M. (2014). The prospects of biolubricants as alternatives in automotive applications. *Renewable and Sustainable Energy Reviews, 33*(0), 34-43

Moebus, H. (1986). Piston for internal combustion engines: Google Patents.

Monaghan, M. L. (1988). ENGINE FRICTION — A CHANGE IN EMPHASIS: A new approach which may result in significant fuel consumption gains. *Industrial Lubrication and Tribology, 40*(2), 4-11

Montgomery, D. C. (1982). *Design and analysis of experiments*: Wiley New York.

Munro, R. (1990). Emissions Impossible-The Piston & Ring Support System: SAE Technical Paper.

Nehme, G. N. (2012). The effect of FeF3/TiF3 catalysts on the thermal and tribological performance of plain oil ZDDP under extreme pressure loading. *Wear, 278–279*, 9-17

Noordin, M. Y., Venkatesh, V. C., Sharif, S., Elting, S., & Abdullah, A. (2004). Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel. *Journal of Materials Processing Technology, 145*(1), 46-58

Peng Chang, B., Md Akil, H., Bt Nasir, R., & Khan, A. (2015). Optimization on wear performance of UHMWPE composites using response surface methodology. *Tribology International, 88*, 252-262

Priest, M., & Taylor, C. (2000). Automobile engine tribology—approaching the surface. *Wear, 241*(2), 193-203

Radil, K. C. (2000). The influence of honing on the wear of ceramic coated piston rings and cylinder liners: DTIC Document.

Rajasekhar, P., Ganesan, G., & Senthilkumar, C. (2014). Studies on Tribological Behavior of Polyamide Filled Jute Fiber-Nano-ZnO Hybrid Composites. *Procedia Engineering, 97*(0), 2099-2109

Rastegar, F., & Richardson, D. (1997). Alternative to chrome: HVOF cermet coatings for high horse power diesel engines. *Surface and Coatings Technology, 90*(1), 156-163

Röhrle, M. D. (1995). *Pistons for Internal Combustion Engines: Fundamentals of Piston Technology*: Landsberg/Lech, Germany.

Shahabuddin, M., Masjuki, H. H., Kalam, M. A., Bhuiya, M. M. K., & Mehat, H. (2013). Comparative tribological investigation of bio-lubricant formulated from a non-edible oil source (Jatropha oil). *Industrial Crops and Products, 47*, 323-330

Shuster, M., Mahler, F., & Crysler, D. (1999). Metallurgical and Metrological Examinations of the Cylinder Liner-Piston Ring Surfaces After Heavy Duty Diesel Engine Testing©. *Tribology Transactions, 42*(1), 116-125

Singh, A. K. (2011). Castor oil-based lubricant reduces smoke emission in two-stroke engines. *Industrial Crops and Products, 33*(2), 287-295

Sorate, K., & Bhale, P. (2013). Impact of biodiesel on fuel system materials durability. *J. Sci. Ind. Res, 72*, 48-57

Stachowiak, G., & Batchelor, A. W. (2004). *Experimental methods in tribology* (Vol. 44): Elsevier.

Stachowiak, G., & Batchelor, A. W. (2013). *Engineering tribology*: Butterworth-Heinemann.

Stachowiak, G. W., Batchelor, A. W., & Stachowiak, G. B. (2004). 2 - Simulation of Wear and Friction. In A. W. B. Gwidon W. Stachowiak & B. S. Grazyna (Eds.), *Tribology Series* (Vol. Volume 44, pp. 13-23): Elsevier.

Sulek, M., Kulczycki, A., & Malysa, A. (2010). Assessment of lubricity of compositions of fuel oil with biocomponents derived from rape-seed. *Wear, 268*(1), 104-108

Tandon, A., Kumar, A., Mondal, P., Vijay, P., Bhangale, U., & Tyagi, D. (2011). Tribological Issues Related to the Use of Biofuels: A New Environmental Challenge. *British Journal of Environment and Climate Change, 1*(2), 28

Taylor, C. M. (1993). Engine Bearings: Background and Lubrication Analysis. In C. M. Taylor (Ed.), *Tribology Series* (Vol. Volume 26, pp. 89-112): Elsevier.

Terheci, M., Manory, R., & Hensler, J. (1995). The friction and wear of automotive grey cast iron under dry sliding conditions Part 1-relationships between wear loss and testing parameters. *Wear, 180*(1), 73-78

Thames, S. F., & Yu, H. (1999). Cationic UV-cured coatings of epoxide-containing vegetable oils. *Surface and Coatings Technology, 115*(2–3), 208-214

Ting, L. (1993). Development of a Reciprocating Test Rig for Tribological Studies of Piston Engine Moving Components-Part II: Measurements of Piston Ring Friction Coefficients and Rig Test Confirmation: SAE Technical Paper.

Truhan, J. J., Qu, J., & Blau, P. J. (2005). A rig test to measure friction and wear of heavy duty diesel engine piston rings and cylinder liners using realistic lubricants. *Tribology International, 38*(3), 211-218

Tung, S. C., & McMillan, M. L. (2004). Automotive tribology overview of current advances and challenges for the future. *Tribology International, 37*(7), 517-536

Urabe, M., Tomomatsu, T., Ishiki, K., Takiguchi, M., & Someya, T. (1998). Variation of Piston Friction Force and Ring Lubricating Condition in a Diesel Engine with EGR: SAE Technical Paper.

Utlu, Z. (2007). Evaluation of Biodiesel Fuel Obtained from Waste Cooking Oil. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 29*(14), 1295-1304

Wakuri, Y., Soejima, M., Ejima, Y., Hamatake, T., & Kitahara, T. (1995). Studies on friction characteristics of reciprocating engines: SAE Technical Paper.

Wang, Y., & Tung, S. C. (1999). Scuffing and wear behavior of aluminum piston skirt coatings against aluminum cylinder bore. *Wear, 225*, 1100-1108

Willing, A. (2001). Lubricants based on renewable resources – an environmentally compatible alternative to mineral oil products. *Chemosphere, 43*(1), 89-98

Yaakob, Z., Mohammad, M., Alherbawi, M., Alam, Z., & Sopian, K. (2013). Overview of the production of biodiesel from Waste cooking oil. *Renewable and Sustainable Energy Reviews, 18*(0), 184-193

Zeman, A., Sprengel, A., Niedermeier, D., & Späth, M. (1995). Biodegradable lubricants—studies on thermo-oxidation of metal-working and hydraulic fluids by differential scanning calorimetry (DSC). *Thermochimica Acta, 268*(0), 9-15

Zhang, J., & Li, H. (2016). Influence of manganese phosphating on wear resistance of steel piston material under boundary lubrication condition. *Surface and Coatings Technology, 304*, 530-536

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*(0), 167-173