Tribology Investigation of Automotive Air Condition (AAC) Compressor by using Al_2O_3/PAG Nanolubricant

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ABSTRACT

Lubrication is a requisite for any mechanical equipment that moved to avoid wear of sliding parts and enhance the equipment operation consistency. The objective of this study was to seek a new improved automotive air conditioning (AAC) compressor lubricant to enhanced AAC performances. The type of compressor is piston type, Sanden SD 7H10,that normally used by Malaysia compact car. The tribological investigation was focusing on Coefficient of friction and wear rate. The wear rate and coefficient of friction (COF) of Alumina/Polyalkylene glycol (Al_2O_3/PAG) nanolubricant were evaluated employing reciprocating test conditions to replicate a piston ring/cylinder liner contact following the ASTM G 181-11 Standard. Al_2O_3 nanoparticle was dispersed in PAG lubricant for volume concentrations between 0.006 to 0.014 vol %. Al_2O_3/PAG nanolubricant with 0.010 % vol. concentration showed the best reduction of frictional power loss. The enhancement of power saving due to frictional losses was up to 7.59 % compared to pure PAG lubricant. Furthermore, the wear rate of piston liner

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reduced by 33.39 %. Al_2O_3 nanoparticles in this circumstances, performed as a solid lubricant to reduce wear. These results show potential approach to enhance the AAC performance, save automotive fuel and elongated the life span for AAC compressor.

Keywords: *Nanolubricant, Alumina, Coefficient of friction, wear rate*

Introduction

Lubrication is a compulsory for mechanical equipment to avoid wear of sliding parts and improving the equipment operation consistency. Mechanical systems with sliding contacts commonly fail due to surface wear at the sliding boundary [1]. Lubricants with varied properties were created in order to be utilised in many applications such as transportation, heavy industries, energy generation and refrigeration system especially in compressor. Many researchers are focusing their works in enhancing lubricant properties to increase the energy efficiency. Recent nanofluid technology is employed to increase lubricant efficiency by dispersing nanoparticle in lubricant base.

Apart studied by Sharif et al [2], low number of research enhancing performance by employing nanolubricant in automotive air conditoning (AAC) system is recorded. In refrigeration system in general, scientists like Bi et al. [3], Kumar and Elansezhian [4] and Yusof et al. [5] studied the benefits of nanolubricant in enhancing efficiencies of refrigeration equipment. Bi et al. [3] showed that Titanium oxide (TiO_2) nanolubricant enhance energy saving by 25 % in domestic refrigerator. Further, Yusof et al. [5] studied the used of Alumina/Polyolester (Al_2O_3/POE) nanolubricant in domestic refrigerator and observed that 2.1 % energy saving was attained. Kumar and Elansezhian [4] investigated the vapor compression system using Alumina (Al_2O_3) nanolubricant and the authors achieved an enhancement of 10.32 % in term of energy efficiency. In general development of nanorefrigerant/ nanolubricant, type of refrigerant based and its performance and energy improvement reviewed by Redhwan et al. [6] and Azmi et al. [7].

This recent work studied the tribological properties of Al_2O_3/PAG nanolubricant at low volume concentrations. The friction and wear rate study were carried out to assess the declining friction and anti-wear abilities of these Al_2O_3 nanoparticle. The reduction of COF and wear rate employing Al_2O_3/PAG nanolubricant been compared with pure PAG and been depicted in percentage enhancement.

Material

The recent work used Alumina (Al_2O_3) nanoparticles as additive to the AAC lubricant based which is Polyalkylene Glycol (PAG). Al_2O_3 procured in nano powder form which in 13nm average particle size, 99.8 % trace metal basis and white in colour. Field Emission Scanning Electron Microscope (FESEM) analysis as depicted in Figure 1 used in confirming the average size of the Al_2O_3 nanoparticle size. While PAG lubricant act as based is commonly used in R134a refrigerant automotive air conditioning (AAC) compressor. The properties of Al_2O_3 nanoparticles and PAG lubricant are shown in Table 1.

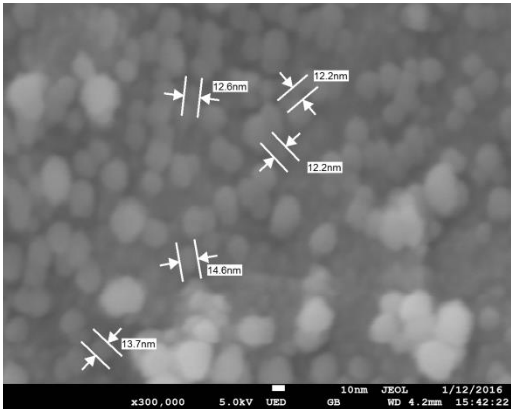


Figure 1: FESEM analysis of 13nm average size of Al_2O_3 nanoparticle

Table 1: Properties of Al_2O_3 nanoparticles and PAG 46 lubricant [8-11]

Property	Al_2O_3 Nanoparticle	PAG 46
Physical form	Spherical Powder	Synthetic Oil
Colour	White	Clear
Density, $g.cm^{-3}$@ 20.0°C	4.0	0.9954
Thermal Conductivity, $W\ m^{-1}\ k^{-1}$ @ 40°C	40	0.147
Kinematic viscosity, cSt @ 40°C	-	41.4-50.6

While Aluminium Al 2024 was used as sample plate in performing the investigation of tribology. The properties of aluminium Al 2024 are shown in Table 2.

Table 2: Properties of Aluminium Alloy, Al 2024 [12]

Properties	Al 2024
Density, $g.cm^{-3}$	2.78
Ultimate tensile strength, MPa	470
Yield Strength, MPa	280
Hardness (Rockwell)	75

Methodology

In this section, preparation and stability evaluation of nanolubricant will be elaborated. Preparation of sample plate and steps in investigating tribology will be discussed in detail.

Preparation and Stability Evaluation of Nanolubricant

In the present study, two-step method was used in preparing nanolubricant. Equation (1) used to determined volume concentration of nanolubricant.

$$\phi = \frac{m_p / \rho_p}{m_p / \rho_p + m_L / \rho_L} \times 100 \tag{1}$$

Where, ϕ is the volume concentration in percent, m_p and m_L are the masses of the nanoparticle and lubricant, respectively; and ρ_p and ρ_L are the density of the nanoparticle and density of the lubricant, respectively. Five (5) samples of Al_2O_3 nanoparticles with volume concentration of 0.006 to 0.014% each were mixed with PAG by using a magnetic stirrer at the speed of 300 rpm for 30 minutes at room temperature with. Then the samples were sonicated for one and half hours. Ultrasonication is an external vibration induced that helps the particles to overcome the van der Waals force bonding. In all samples, surfactant was not used.

The stability Al_2O_3/PAG nanolubricant was determined by observing the relative stability of colloidal using sedimentation photograph capturing methods. The observation was carried for a period of a month. This is the primary method that are been used in determining stability of colloidal [13]. The qualitative observation data then validated by using quantitative measurement. The second stability method is by using UV-Vis Spectrophotometer. Similar approach were done by several other researchers [14-16].

Tribological properties evaluations

The compressor type used in this project is Sanden SD 7H10, piston type compressor [17]. Prior the tribology test, the AAC compressor was disassembled to determine the type of cylinder wall's material by Positive Material Identification (PMI) method. Further examination on hardness and surface roughness was also done. Table 3 showed the outcome of the investigations.

Table 3: Properties of AAC compressor cylinder wall

Properties	Outcome
Material	Al 2024
Hardness (Rockwell B)	74.52
Surface roughness, Ra, (μm)	0.121

Similar type of material was also considered by [18]. Then the tribology experiment was performed under lubricated reciprocating sliding condition in compliance to ASTM G 181-11 Standard [19]. Coefficient of friction (COF) and specific wear rate of compressor employing Al_2O_3/PAG nanolubricant were assessed by reciprocating liner test machine as shown in Figure 2. Tribology investigations comprises of reciprocating movement analogous to the piston head sliding to the cylinder wall under the AAC compressor operating state. The friction occurred when the duo cast iron rings fitted to piston head made a rubbing contact to the compressor cylinder wall. Significant control factors such as loads, piston movement speed and operating time were considered in this experiment. According to Cesur et al. [20], low speed generate larger friction, henceforth, low speed interval of 200 to 300 rpm were chosen. While the desired loads were attained by applying weight on to the bearing lever directly above the sample plate. The weight ranging from 2.0 to 10.0 kg were considered while the operating time for each run was 2 minutes. Figure 2 below depicted the schematic diagram of the tribology test rig that was used in this tribological properties evaluation.

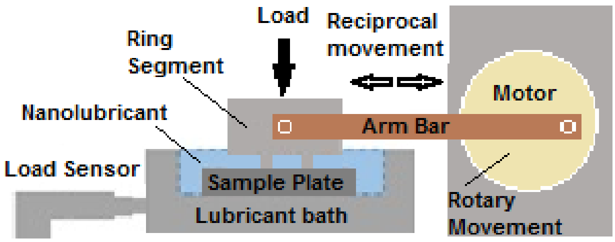


Figure 2: Schematic diagram for Tribology Test rig

The coefficient of friction (COF) is been determined by Equation (2) below:

$$\mu_k = \frac{F_k}{F_n} \tag{2}$$

Where μ_k is coefficient of kinetic friction, F_k is applied force and F_n is the load.

While, the specific wear rate (ω_s) of the specimen was calculated using Equation (3) below:

$$\varpi_s = \frac{\Delta V}{F_n \times S_s} \tag{3}$$

Where F_n is normal load (N), which ΔV and S_s are determined by using Equation (4) and Equation (5) respectively.

$$\Delta V = \frac{1}{\rho}(w_0 - w_1) \tag{4}$$

$$S_s = 2f \times L \times t \tag{5}$$

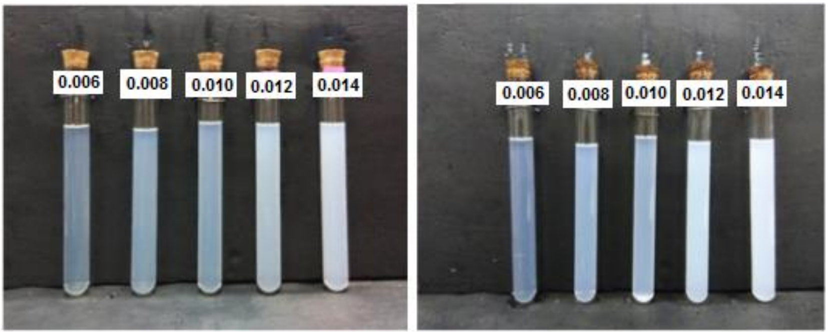
Where ρ is density of plate, w_0 and w_1 are the plate weight before and after the experiment, S_s is the distance travel, f is the frequency, L is the stroke length and t is time in second.

Results and Discussion

Stability of nanolubricant

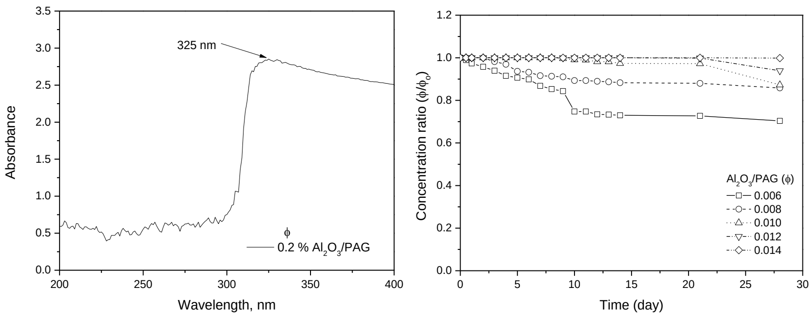
Figure 3 show the sedimentation photograph of Al_2O_3/PAG nanolubricant with five different concentration after preparation and after 28 days of preparation. From the Figure 3, even though small sedimentation was observed in the sample, the Al_2O_3/PAG nanolubricant for all volume concentrations is stable since it still in homogenous form even after a month of preparation.

Parallel to the photographed sedimentation method, UV-vis spectrometer was also being carried out to validated the stability of the colloidal quantitatively. The colloidal stability of these five samples were tested based on peak value of absorbance which is 325 nm wavelengths as shown in Figure 4(a). The immediate concentration over initial concentration ratio against the sedimentation time were plotted and depicted in Figure 4(b). Details steps were explained in [21, 22]. From the graph, it shows that, higher concentration reflects better stability. 0.014 % vol. concentration of Al_2O_3/PAG nanolubricant maintain the concentration ratio above 95 %. While the lowest concentration (0.006 % vol. concentration) maintaining the ratio concentration above 70 % even after 28 days. Hence it can be concluded that the Al_2O_3/PAG nanolubricant for all concentrations in this work were stable.



(a) (b)

Figure 3: Five samples of Al_2O_3/PAG (a) Just after preparation (b) After 28 days



(a) (b)

Figure 4: (a) The absorbance value for 0.006 % Al_2O_3/PAG (b)Concentration ratio against sedimentation time for Al_2O_3/PAG nanolubricant

Tribological investigation

Figure 5 shows the graph of weight against average COF and specific wear rate for the different speed. Referring to the Figure 5, the value of average COF decreases with the increasing of the weight where the decrease pattern is inversely exponential. This could be explained by referring to the Equation (2). The weight herein represents the f_n value in the Equation (2) which is inversely proportionate to the COF value. Further investigation show that different speed could not significantly affect COF value. the Specific wear rate, on the other hand increases with the increasing of weight. The increase is in linear pattern for all three speeds been studied. The speed inversely effects the specific wear rate where the lower the speed the greater the wear rate. Hence the higher the weight and the lower the rpm would give greater damage to the surface cause by the wear rate, while the higher the weight the lower the average of COF.

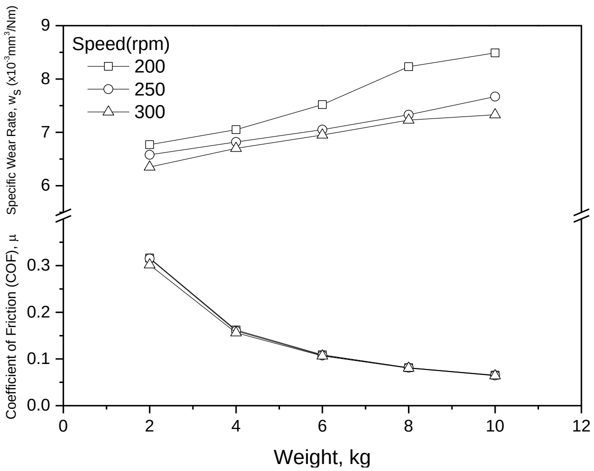


Figure 5: The effect of weight towards the average COF and Specific wear rate

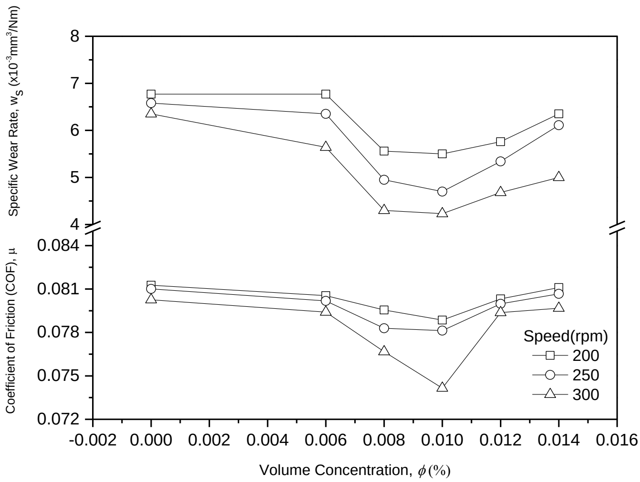


Figure 6: The effect of volume concentration towards the COF and Specific wear rate

Figure 6 depict the effect of Al_2O_3/PAG concentration towards the average COF and specific wear rate. From the graph, it shows that increasing the concentration will reduce the COF. The decreasing pattern is continued up to 0.010 % vol. concentration. Similar to the COF pattern, the value of specific wear rate is decrease with increasing of volume concentration up to 0.010 %. This may due to the creation of tribo-film on worn surfaces, stand-in as a solid lubricant or an ultra-thin lubricating coating that reduce shear stress. The rolling action of nanoparticles between the contact surfaces leads to a change from pure sliding friction to rolling friction, that is a mechanism that may provides a decrease in the average COF and specific wear rate. While COF and wear rate decrease with adding nanoparticle into the lubricant, further increasing volume concentration diminished the good effect toward COF and wear rate value. It been portrayed by the graph, which after 0.010 % volume concentration, the COF and the wear rate value again increase with the increasing of volume concentration of nanolubricant. The identical pattern is observed by Ali et al [23], where the authors stated that optimum concentration of nanoparticle is a crucial parameter since surplus concentration would give negative impact towards the COF and wear rate. For both cases, The lower the speed, the higher the value of the COF and the wear rate. Hence the Al_2O_3/PAG nanolubricant with 0.010 % volume concentration is the optimum concentration and this concentration should be used in further study the performance of the AAC system.

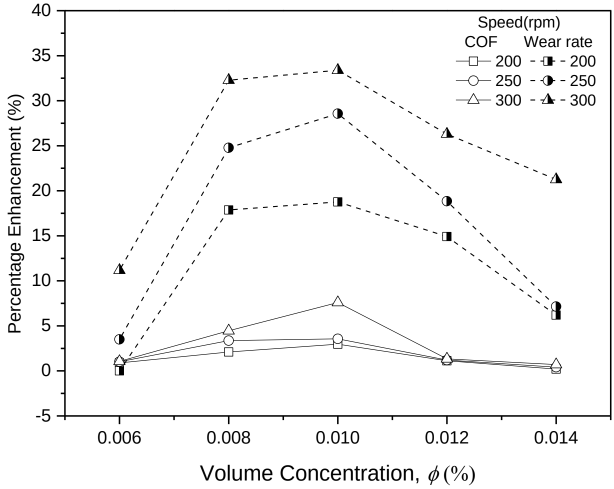


Figure 7: The effect of volume concentration towards the percentage enhancement of the average COF and the Specific wear rate

Further study on the effect of volume concentration towards the tribological behaviour percentage enhancement is carried out. The COF and the wear rate value for each nanolubricant concentration is compared to the base PAG lubricant. Figure 7 depict the percentage enhancement of tribological behaviour for COF and specific wear rate against the Al_2O_3/PAG nanolubricant concentration. The lower part of the graph shows the enhancement of average COF at 0.006 to 0.014 % volume concentration for the weight of 8 kg**.** The highest COF enhancement achieved is 7.59 % at 0.010 % volume concentration for the speed of 300 rpm. While the average COF enhancement of 2.14 % was attained. Further, on the upper part of the graph in Figure 7 shows the enhancement of specific wear rate for five different concentration in the range of 0.006 up to 0.014 % at 2 kg load. The highest and average enhancement of specific wear rate were achieved at 33.39 % and 17.67 % respectively for 300 rpm speed and 0.010% volume concentration. The volume concentration of Al_2O_3/PAG nanolubricant give significant effect toward the reduction of tribological behaviour. Further investigations on parametric studies show that, for both cases of tribological investigations, 0. 010 % Al_2O_3/PAG volume concentration nanolubricant give the maximum reduction in COF and wear rate. From the graph also shows that the speed of 300 rpm give the optimum result of reduction for both tribology behaviour. Even though weight parameter give effect on both COF and specific wear rate as shown earlier in Figure 5, no dominant weight parameter reflected on the enhancement of both tribology behaviour. The optimum reduction of COF is when 8 kg of load been used while 2 kg gave highest impact on wear rate reduction.

Conclusions

In this work, tribological characteristic of AAC compressor employing Al_2O_3/PAG nanolubricant was valuated. It was found that the COF was reduced up to 7.59 % with average of 2.14 %. While the specific wear rate was declined up to 33.39 % with average of 17.67 % by the usage of Al_2O_3/PAG nanolubricant with 0.010% volume concentration. This results manifestation plausible approach to save automotive fuel and elongated the life span to the AAC compressor. Further investigation of AAC performance using Al_2O_3/PAG nanolubricant with 0.010% volume concentration is recommended.

Acknowledgments

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References

[1] J. Williams and H. Le, "Tribology and MEMS," *Journal of Physics D: Applied Physics,* vol. 39, no. 12, p. R201, 2006.

[2] M. Z. Sharif, W. H. Azmi, A. A. M. Redhwan, R. Mamat, and T. M. Yusof, "Performance analysis of SiO_2/PAG nanolubricant in automotive air conditioning system," *International Journal of Refrigeration,* 2017.

[3] S.-s. Bi, L. Shi, and L.-l. Zhang, "Application of nanoparticles in domestic refrigerators," *Applied Thermal Engineering,* vol. 28, no. 14, pp. 1834-1843, 2008.

[4] D. S. Kumar and R. Elansezhian, "Experimental study on Al_2O_3-R134a nano refrigerant in refrigeration system," *International Journal of Modern Engineering Research,* vol. 2, no. 5, pp. 3927-3929, 2012.

[5] T. Yusof, A. Arshad, M. Suziyana, L. Chui, and M. Basrawi, "Experimental Study of a Domestic Refrigerator with POE-Al_2O_3

Nanolubricant," *International Journal of Automotive & Mechanical Engineering,* vol. 11, 2015.

[6] A. A. M. Redhwan, W. H. Azmi, M. Z. Sharif, and R. Mamat, "Development of nanorefrigerants for various types of refrigerant based: A comprehensive review on performance," *International Communications in Heat and Mass Transfer,* vol. 76, pp. 285-293, 8// 2016.

[7] W. H. Azmi, M. Z. Sharif, T. M. Yusof, R. Mamat, and A. A. M. Redhwan, "Potential of nanorefrigerant and nanolubricant on energy saving in refrigeration system – A review," *Renewable and Sustainable Energy Reviews,* vol. 69, pp. 415-428, 3// 2017.

[8] W. L. Brown, "Polyalkylene glycols," *CRC Handbook of Lubrication and Tribology,* vol. 3, pp. 253-267, 1993.

[9] Dow, "Material Safety Data Sheet," *Ucon Refrigerant Lubricant 213,* 2013.

[10] M. Z. Sharif, W. H. Azmi, A. A. M. Redhwan, and R. Mamat, "Investigation of thermal conductivity and viscosity of Al_2O_3/PAG nanolubricant for application in automotive air conditioning system," *International Journal of Refrigeration,* 2016.

[11] A. M. Khdher, N. A. C. Sidik, W. A. W. Hamzah, and R. Mamat, "An experimental determination of thermal conductivity and electrical conductivity of bio glycol based Al_2O_3 nanofluids and development of new correlation," *International Communications in Heat and Mass Transfer,* vol. 73, pp. 75-83, 4// 2016.

[12] ASTM B209-14, ASTM International, West Conshohocken, PA, " Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate," *ASTM International,* 2014.

[13] A. Ghadimi, R. Saidur, and H. S. C. Metselaar, "A review of nanofluid stability properties and characterization in stationary conditions," *International Journal of Heat and Mass Transfer,* vol. 54, no. 17–18, pp. 4051-4068, 8// 2011.

[14] M. K. Abdolbaqi, W. H. Azmi, R. Mamat, K. V. Sharma, and G. Najafi, "Experimental investigation of thermal conductivity and electrical conductivity of BioGlycol–water mixture based Al_2O_3 nanofluid," *Applied Thermal Engineering,* vol. 102, pp. 932-941, 6/5/ 2016.

[15] N. N. M. Zawawi, W. H. Azmi, A. A. M. Redhwan, M. Z. Sharif, and K. V. Sharma, "Thermo-physical properties of Al_2O_3-SiO_2/PAG composite nanolubricant for refrigeration system," *International Journal of Refrigeration,* vol. 80, pp. 1-10, 8// 2017.

[16] A. A. M. Redhwan, W. Azmi, M. Sharif, and N. Zawawi, "Thermal conductivity enhancement of Al_2O_3 and SiO_2 nanolubricants for application in automotive air conditioning (AAC) system," in

MATEC Web of Conferences, 2017, vol. 90, p. 01051: EDP Sciences.

[17] A. A. M. Redhwan, W. Azmi, M. Sharif, and F. Y. Hagos, "Development of nanolubricant automotive air conditioning (AAC) test rig," in *MATEC Web of Conferences*, 2017, vol. 90, p. 01050: EDP Sciences.

[18] M. R. A. Aziz, N. B. Baba, and M. L. S. Shafee, "Compatibility Study of Replacement Material for Cold Cutting Machine," in *Advanced Materials Research*, 2014, vol. 875, pp. 1539-1543: Trans Tech Publ.

[19] ASTM G181-11, ASTM International, West Conshohocken, PA,, " Standard Test Method for Conducting Friction Tests of Piston Ring and Cylinder Liner Materials Under Lubricated Conditions," *ASTM International,,* Standard 2011.

[20] İ. Cesur, V. Ayhan, A. Parlak, Ö. Savaş, and Z. Aydin, "The Effects of Different Fuels on Wear between Piston Ring and Cylinder," *Advances in Mechanical Engineering*, vol. 6, p. 503212, 2014/01/01 2014.

[21] A. A. M. Redhwan, W. H. Azmi, M. Z. Sharif, R. Mamat, and N. N. M. Zawawi, "Comparative study of thermo-physical properties of SiO_2 and Al_2O_3 nanoparticles dispersed in PAG lubricant," *Applied Thermal Engineering*, vol. 116, pp. 823-832, 4// 2017.

[22] M. Sharif, W. Azmi, A. Redhwan, and N. Zawawi, "Preparation and stability of silicone dioxide dispersed in polyalkylene glycol based nanolubricants," in *MATEC Web of Conferences*, 2017, vol. 90, p. 01049: EDP Sciences.

[23] M. K. A. Ali, H. Xianjun, L. Mai, C. Qingping, R. F. Turkson, and C. Bicheng, "Improving the tribological characteristics of piston ring assembly in automotive engines using Al_2O_3 and TiO_2 nanomaterials as nano-lubricant additives," *Tribology International*, vol. 103, pp. 540-554, 11// 2016.