The effect of Al₂O₃/PAG nanolubricant towards automotive air conditioning (AAC) power consumption

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Abstract. The usages of Automotive Air Conditioning (AAC) today is vital because of the hot and humid climate. The AAC is used to provide comfort in the automotive cabin temperature, consequently, increases fuel consumption, and release significant amount of CO₂, and greenhouse gas into the air. Nanotechnologies could be employed into AAC system via lubricant compressor which can decrease power consumption, eventually increase power saving. The main objective of this paper is to experimentally investigate the effect of Al₂O₃/PAG nanolubricant on the power consumption. The study on the stability and characteristic of the Al₂O₃/PAG nanolubricant has been done prior the experiment. The result shows that the Al₂O₃/PAG nanolubricant is stable event after 28 days with concentration ratio above 70%. The highest power saving percentage of 23.89% is achieved when the AAC system is operated with 0.010% Al₂O₃/PAG nanolubricant. Further, it has been shown that the condenser pressure and evaporator pressure are correlated with the increment of the power consumption with average deviation of 3.129% and 2.919%, respectively. Finally, the power consumption of AAC system reduce with the usage of the Al₂O₃/PAG nanolubricant at low concentration.

1. Introduction

Air conditioning is essential for a vehicle. This is due to the unpredictable weather conditions, especially in countries like Malaysia that have hot and humid weather all year long. In addition, global warming is also a major factor in increasing the use of air conditioning in vehicles. Regular use of air conditioning results in increased load on the engine and thus increases fuel consumption. Therefore, over the last decade, researchers and engineers have been working hard on air-conditioning technology to maximize energy efficiency as well as prioritize the impact on environment. Many efforts have been made by various researchers to improve and optimize the Automotive Air Conditioning (AAC) system through major component improvements as well as in terms of operating systems and electronic control management [1]. However, the authors argue that the working fluid used in the AAC system can still be improved. To date, recent studies have shown that the performance of the vapour
compression system can be improved if nanoparticles are added into the refrigerant or into the compressor [2].

Given the current trend, many researchers prefer to use nanoparticles in a compressor because there are not many refrigerants with boiling point higher than room temperature. The lubricating properties used in the AAC compressor change for the better when nanoparticles are mixed with lubricants. According to previous studies, adding nanoparticles in a lubricant compressor promotes the enhancement of the lubricant mixture, having the advantage of thermal properties and improved tribological performance [3-6]. The main idea of using nanolubricant is to reduce friction by improving its rheological properties; thus, reducing the work done by the compressor and improving the efficiency of the system. In addition, nanofluids usually have better thermal conductivity and thus improve heat transfer performance. Therefore, many studies involving cooling systems and lubrication systems have been conducted using nanotechnology to improve system performance.

The first attempt to prove improvement of thermal fluid nanofluid is with the use of Al_2O_3 nanoparticles dispersed in water [7]. With reference to the previous statement, Ahmadi Hojjat tested the effectiveness of nanoparticle nanolubricant use CNT as additives. The results of the experiment, shows the thermal conductivity and the flash point increased by 13.2% and 6.7%, respectively, when the base lubricant was compared with the nanolubricant 0.1% weight percentages [8]. In the previous experiment, the thermal-physical properties of Al_2O_3 nanoparticles dispersed into PAG have been measured. An enhancement of thermal conductivities and the viscosity ratio about 1.04 and 7.58 respectively [9]. In another experiment, the heat transfer performance also enhance up to 129% when the low concentration R134a/nanolubricant was used instead of R134a/polyolester [10]. In one of the latest finding, it has been shown that a vapour compression system operates at different working pressure gives different result for the compression work thus the power consumption [11]. Basically, to reduce the power consumption of the AAC system, the system is to operate at lower working pressure or lower pressure ratio at a considerable cooling performance. Various experimental studies were conducted to investigate the properties [12, 13] and performance of nanolubricant in refrigeration system.

The objective of this paper to analyse the effect of low concentration Al_2O_3/PAG nanolubricant to reduce the power consumption of the AAC system. The best method to make a stable Al_2O_3/PAG nanolubricant was developed and thoroughly analyse using quantities and qualitative study. The next phase of this work was a systematic experimental investigation of AAC system, which was conducted on a modified automotive air conditioning system for the purpose of this work. The influences of evaporator and condenser pressure were considered to study the effect of nanolubricant as a power consumption reduction and power saving potential in AAC system.

2. Methodology

The methodology is divided into three parts: preparation of Nanolubricant, AAC experimental setup and AAC Power Consumption analysis

2.1. Preparation of nanolubricant

The nanoparticles used were Al_2O_3; with a purity of 99.8%, and 13 nm in size which is obtained from Sigma-Aldrich company. Characterization of nanoparticles such as the size and shape of nanoparticles was confirmed using electron microscopy scanning (FESEM) imaging technique. Figure 1 shows the FESEM image at a magnification of X 300,000. As a result of this scan, it has been determined that Al_2O_3 nanoparticles have a spherical shape with an average size of about 13 nm. The basic properties of Al_2O_3 are shown in more detail in table 1 [14, 15]. The AAC system used in experimental test setup using PAG oil obtained from Denso Corporation. The manufacturer of the AAC system recommends oil type PAG ND8 as it is more compatible with the material used such as aluminum pipe and rubber in the pipe connection. The basic properties of the lubricant PAG 46 at atmospheric pressure are shown in table 2 [16, 17].
Table 1. Properties of Al₂O₃ nanoparticles.

| Property                        | Al₂O₃     |
|---------------------------------|-----------|
| Molecular mass, g · mol⁻¹       | 101.96    |
| Average Particle diameter, nm   | 13        |
| Density, kg · m⁻³               | 4000      |
| Thermal Conductivity, W(m · K)⁻¹| 36        |
| Specific heat, J(kg · K)⁻¹      | 773       |

Table 2. Properties of Polyalkylene glycol (PAG 46) lubricant.

| Property                        | PAG 46   |
|---------------------------------|----------|
| Density, g · cm⁻³ @ 20 °C       | 0.9954   |
| Flash Point, °C                 | 174      |
| Kinematic viscosity, cSt @ 40 °C| 41.4-50.6|
| Pour Point, °C                  | -51      |

Figure 1. FESEM image of dry Al₂O₃ nanoparticle at X 300,000 magnifications.

Nanolubricant is prepared using the two-step preparation method. Al₂O₃ nanoparticles were mixed into the oil PAG using a magnetic stirrer for 1 hour. Thereafter, the nanolubricant suspension is further stabilized again uses high frequency ultrasonic vibration in the ultrasonic bath (model: FB15051 Fisherbrand) for 1.5 hours; to solve the agglomeration and produce a more uniform dispersion. In another paper, the same method in preparing their PAG-based nanolubricant [9, 18-20]. The stability of nanolubricant was one of the main concerns that affected the properties of nanolubricant and their operation in an application system. The qualitative and quantitative study was used in this paper to assess the stability of the Al₂O₃/PAG suspension. Stabilities for nanolubricant were tested using sedimentation visual observation and UV-Vis Spectrophotometer.

2.2. AAC experimental setup
The original components of the automotive air conditioning system were used to build this experimental test setup. It is adjusted with the original position and condition inside the engine chamber to mimic the situation inside the actual vehicle. The main components of the AAC experimental test system are piston-type compressors, multichannel type evaporator and condenser, and thermostatic expansion valve. The evaporator has been immersed into the cabin calorimetric insulated water containing heated water (60 L capacity) which act as heat load to the evaporator. The
cooling capacity and the refrigeration mass flow rate are measured by computing the difference between the water inlet and outlet enthalpy in accordance to the standard of Standard 41.9-2000 (Calorimeter Test Methods for Mass Flow Measurements of Volatile Refrigerants). In this experiment, a 2.2 kW, 3-phase electric motor was used to rotate the pulley connected to the compressor through a belting system. Frequency inverters have been used to control and change the speed of motor rotation. Temperature and pressure were measured using a T-type thermocouple as well as a pressure sensor to read the amount of enthalpy at different points of the cooling cycle, with their accuracy being ± 0.1 °C and ± 1 kPa. A 3-phase power analyser (Model: Lutron DW-6092) was installed on the motor induction to monitor and measure the power consumption of the AAC system with a precision of ± 0.001 kW. The calibration method was used for all measurement devices in this study and the device has been proven to work perfectly. A schematic diagram for the AAC test setup and power analyser is shown in figure 2 and figure 3.

![Schematic diagram of AAC system](image1)

**Figure 2.** Schematic diagram of AAC system.

![Power analyser](image2)

(a) Front view  
(b) Connection measurement diagram

**Figure 3.** DW 6092 Lutron power analyser.
2.3. AAC power consumption analysis
For ease of calculation, it is assumed that no pressure drops in the condenser, evaporator, and all refrigerant lines in the AAC system. The condensation and evaporation pressure is estimated to be equal to the pressure exerted and the suction measured by the pressure gauge. The data for temperature and pressure are monitored and collected in the data acquisition software, ADAMView.

The test setup continued for 20 minutes for the system to reach a steady-state, so the test data was retrieved, and the logs were taken for 10 minutes after that. Data for pressure and temperature for each given point were used to calculate the enthalpy values using the refrigerant properties table. The experimental procedure was then replicated for various compressor speeds; it varies between 900 and 2100 rpm with 300 rpm intervals. After completing one refrigerant charge, the process is repeated for different refrigerant charges; varies between 90 and 170 grams. After the experiment with all refrigerant charges is completed, the procedure is repeated for different concentrations of Al$_2$O$_3$/PAG nanolubricant. In this experimental work, the reliability and consistency of the data are considered. Thus, each set of experiments was repeated three times.

Power saving ($E_{saving}$) is determined by evaluating the relative power consumption of the AAC system using Al$_2$O$_3$/PAG nanolubricant ($\dot{W}_{NL}$) against the AAC system that employed the PAG lubricant ($\dot{W}_{PAG}$) as shown in equation (1).

$$E_{saving} = \frac{\dot{W}_{NL} - \dot{W}_{PAG}}{\dot{W}_{PAG}} \times 100\%$$

Effective power consumption ($\dot{W}_{eff}$) for pure PAG ($\dot{W}_{PAG}$) and Al$_2$O$_3$/PAG nanolubricant($\dot{W}_{NL}$) is determined by equation (2).

$$\dot{W}_{eff} = \dot{w}_{\text{with load}} - \dot{w}_{\text{w/o load}}$$

where $\dot{W}_{eff}$ is the effective power consumption by the compressor at constant speed with exception of mechanical losses and magnetic losses of motor [21, 22]. Further, $\dot{w}_{\text{with load}}$ is the power consumption measured when the magnetic clutch of the compressor is engaged. Meanwhile, $\dot{w}_{\text{w/o load}}$ is the power consumption measured when the compressor magnetic clutch is disengaged, and the losses is associated in the measurement. DW 6092 Lutron power analyzer as shown in figure 2 is used to measure the electrical power consumption of the 3-phase induction motor which drives the AAC compressor. The connection measurement diagram of the power analyzer is shown in figure 2(b).

3. Results and discussion
The result will discuss on the stability of nanolubricant, power saving and relation between the power consumption and condenser/evaporator pressure.

3.1. Stability of nanolubricant
The Al$_2$O$_3$/PAG nanolubricant with concentrations between 0.006% and 0.2% were prepared with 1.5 hours sonication time. The concentration ratio against the sedimentation time was plotted for 28 days and shown in figure 4. From the graph, apart from the 0.006% concentration, all other Al$_2$O$_3$/PAG nanolubricant concentration ratios $\phi$, were observed to be above 85%. Even though the Al$_2$O$_3$/PAG nanolubricant with 0.006% concentration shows the lowest stability in terms of the concentration ratios $\phi$, but the concentration ratio $\phi$, is kept above 70% even after 28 days. A comparable stability condition was also suggested by [23] and [24]. Hence it can be concluded that the Al$_2$O$_3$/PAG nanolubricant are stable for all concentrations.

Two sets of Al$_2$O$_3$/PAG nanolubricant which were categorized as low and high-volume concentrations were put aside and kept stationary in test tubes. The test tubes were kept without interruption for a period of a month with the help of a black background studio for clear image capture. The observation of the samples was done daily. The photograph image of both samples was captured on the first day of preparation and after a month for qualitative evaluation. Figure 5(a) shows the
sedimentation photograph of Al$_2$O$_3$/PAG nanolubricant for the first day of preparation and figure 5(b) shows the sedimentation photograph of Al$_2$O$_3$/PAG after a month of preparation for low and high concentrations. Both photograph images were compared and from the image observed, no sedimentation occurred for both low and high concentrations of Al$_2$O$_3$/PAG nanolubricant. The samples were stable as signs of sedimentation or colour separation had not occurred. Hence, the Al$_2$O$_3$/PAG nanolubricant can be concluded as stable throughout the concentrations.

![Figure 4](image1.png)  
**Figure 4.** Concentration ratio against the sedimentation time for various concentration of Al$_2$O$_3$/PAG nanolubricant.

![Al$_2$O$_3$/PAG sedimentation photographs](image2.png)  
(a) Visual sedimentation for the first day of preparation

![Al$_2$O$_3$/PAG sedimentation photographs](image3.png)  
(b) Visual sedimentation after one month of preparation

**Figure 5.** Al$_2$O$_3$/PAG nanolubricant sedimentation photograph.
3.2. Power saving

Figure 6 shows power consumption as a function of refrigerant charge of 0.010% Al$_2$O$_3$/PAG nanolubricant as compared to pure PAG lubricant for three variants of compressor speed.

![Figure 6. Power consumption as a function of initial refrigerant charge.](image)

At the lower initial refrigerant charge, the power consumption of 0.010% Al$_2$O$_3$/PAG nanolubricant is higher compares to pure PAG lubricant. As the refrigerant charge is added, the differences of the power consumption get lesser till the initial refrigerant charge is 130 g. From 130 g initial refrigerant charge onward, the power consumption differences between Al$_2$O$_3$/PAG nanolubricant and pure PAG lubricant is increased. At higher refrigerant charge conditions, the power consumption of 0.010% Al$_2$O$_3$/PAG nanolubricant is lower compared to pure PAG lubricant. Therefore, 130 g initial refrigerant charge is the interchange point lines of the power consumption between these two kinds of lubricants. At lower initial refrigerant charge, the power consumption of 0.010% Al$_2$O$_3$/PAG nanolubricant is higher compared to pure PAG lubricant due to the compressor requiring harder work to pump the refrigerant at the suction side and to overcome resistance from the viscosity of the Al$_2$O$_3$/PAG nanolubricant. The higher the refrigerant charge, the less work needs to be done by the compressor to pump the refrigerant at the suction side. At the same time, the rolling friction also takes place since refrigerant (hence Al$_2$O$_3$ nanoparticle) are now able to occupy and cover everything in the AAC systems especially inside the compressor. The rolling friction will reduce the COF [25], thus eventually reducing the compressor work. In the absence of Al$_2$O$_3$ nanoparticles in the pure PAG lubricant, the rolling effect does not happen in the compressor. Hence at higher refrigerant charges, the power consumption of the Al$_2$O$_3$/PAG nanolubricant is lower when compared to pure PAG lubricant.

Table 3 shows the percentage of power saving of Al$_2$O$_3$/PAG nanolubricant compared to pure PAG lubricant for 170 g initial refrigerant charge. From the table, it shows that the highest percentage of power saving recorded is 23.89% when the AAC system operates with 0.010% Al$_2$O$_3$/PAG nanolubricant and coupled with 900 rpm compressor speed. The average power saving recorded is 11.38%.

Figure 7 shows the power saving as the function of volume concentration for five variants of compressor speeds. The graph shows that the maximum power saving is achieved when the 0.010% volume concentration of Al$_2$O$_3$/PAG nanolubricant is used in the AAC system with 900 rpm compressor speed. The graph also shows 0.010% volume concentration of Al$_2$O$_3$/PAG nanolubricant is the optimum concentration which gave the highest reading of power saving for all compressor speeds. Hence, it is proven that Al$_2$O$_3$/PAG nanolubricant with 0.010% volume concentration give the best performances to the power saving for the AAC system.
Table 3. Percentage of power saving for Al₂O₃/PAG nanolubricant.

| Speed, Rpm | Volume Concentration, φ (%) | Percentage enhancement (%) |
|------------|-----------------------------|----------------------------|
|            | 0.006 | 0.008 | 0.010 | 0.012 | 0.014 |
| 900        | 5.24  | 16.16 | 23.89 | 11.29 | 9.86  |
| 1200       | 5.79  | 16.75 | 21.76 | 11.85 | 11.07 |
| 1500       | 3.63  | 12.41 | 18.79 | 10.68 | 7.87  |
| 1800       | 4.00  | 13.07 | 16.00 | 10.02 | 6.97  |
| 2100       | 2.80  | 13.61 | 14.53 | 9.14  | 7.26  |

Figure 7. Power saving of Al₂O₃/PAG nanolubricant as a function of volume concentrations.

3.3. Relationship between power consumption and pressure

Figure 8 depicts the evaporator pressure as a function of refrigerant charge while figure 9 shows the condenser pressure as a function of refrigerant charge. From the observation, the pattern of these graphs mimic figure 6 which depicts the power consumption as a function of refrigerant charge. Figure 9 shows that the condenser pressure of Al₂O₃/PAG nanolubricant at 90 g refrigerant charge is higher than pure PAG lubricant and lower at 170 g refrigerant charge. Further investigation on figure 9 reveals that the condenser pressure of Al₂O₃/PAG nanolubricant and pure PAG lubricant lines intersected at 130 g refrigerant charge. A similar intersected pattern is observed for the power consumption graph as depicted in figure 6. Observation of the evaporator pressure as depicted in figure 8 revealed that the evaporator pressure of Al₂O₃/PAG nanolubricant and pure PAG lubricant lines intersected at 140–145 g refrigerant charge. Hence it can be concluded that the condenser pressure graph closely mimics the graph of power consumption. Nevertheless, the evaporator pressure graph also follows a similar pattern with the power consumption graph. Hence both condenser and evaporator pressures can be used to estimate the power consumption utilized by the AAC system.

Accordingly, equation (3) and equation (4) which are developed from the experimental data for the estimation of power consumption related to condenser and evaporator pressures. Other parameters, namely compressor speed, refrigerant charge and Al₂O₃/PAG nanolubricant volume concentration are also considered. Equation (3) is valid for the condenser pressure between 500 kPa to 1123 kPa while equation (4) is valid for the evaporator pressure in the range of 60 to 296 kPa. Both equations shared the same range of other parameters. The compressor speed is in the range of 900 to 2100 rpm, the refrigerant charge is between 90 to 170 g and Al₂O₃/PAG nanolubricant volume concentrations up to 0.014%.
\[
\dot{W}_c = \frac{\dot{W}_{NL}}{W_{PAG}} = 0.1433 \left( \frac{P_{\text{cond}}}{1223} \right)^{0.7205} \left( \frac{N_{\text{comp}}}{2100} \right)^{-0.1442} \left( \frac{m_{\text{ref}}}{170} \right)^{-0.8857} \left( 0.01 + \frac{\phi}{100} \right)^{-0.4318} \tag{3}
\]

\[
\dot{W}_r = \frac{\dot{W}_{NL}}{W_{PAG}} = 0.2644 \left( \frac{P_{\text{evap}}}{296} \right)^{0.5105} \left( \frac{N_{\text{comp}}}{2100} \right)^{0.3142} \left( \frac{m_{\text{RC}}}{170} \right)^{-0.9438} \left( 0.1 + \frac{\phi}{100} \right)^{-0.6567} \tag{4}
\]

Figure 8. Evaporator pressure as a function of initial refrigerant charge.

Figure 9. Condenser pressure as a function of initial refrigerant charge.

The average deviation, standard deviation and maximum deviation for power consumption related to condenser pressure were 3.129%, 4.399% and 3.99% respectively while the estimation of power consumption related to evaporator pressure attained at 2.919%, 3.911% and 3.984% for average deviations, standard deviations and maximum deviations, respectively. The distribution of power consumption related to condenser pressure experimental data compared to regression equations are presented in figure 10. Figure 11 shows the distribution of experimental data compared to regression equations of power consumption related to evaporator pressure. From the graphs, the experimental data is in good agreement with estimated equations.
4. Conclusion
The effect of the Al₂O₃/PAG nanolubricant onto the power consumption of AAC has been investigated. Beforehand, stable Al₂O₃/PAG nanolubricant is established with 1.5 hours sonication. It is found that Al₂O₃/PAG nanolubricant with 0.010% volume concentration give maximum power saving up to 23.89% with average of 18.99%. The relationship between power consumption and AAC condenser/evaporator pressure in mathematical/regression modelling also has been established. It can be concluded that the experimental data is in good agreement with the estimated equations.

Acknowledgments
The authors are grateful to TATI University College, Universiti Malaysia Pahang (UMP) and the Automotive Engineering Centre (AEC) for financial supports given under RDU151411 (RAGS/1/2015/TK0/UMP/03/2) and RDU1603110.

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