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Comparative Study of Single and Composite Nanolubricants in Automotive Air-Conditioning (AAC) System Performance

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Abstract. Various studies by leading experts have shown the effectiveness of nanolubricant in improving the performance of the automotive air conditioning (AAC) system. Along with the advancement of technology, composite nanolubricant have been introduced and have been proven to have better properties than normal nanolubricant. The Al₂O₃-SiO₂/PAG composite nanolubricant have better stability, better heat transfer, and improve tribology characteristic compare to its individual single nanoparticles nanolubricant. However, until now no experiments were conducted to test the effectiveness of composite nanolubricant in the AAC system. An experimental study is then taken by testing the Al₂O₃-SiO₂/PAG in AAC system. The results of this experiment have been compared with results of the previous study that uses Al₂O₃/PAG and SiO₂/PAG in AAC system. It is found that the composite nanolubricant have a high enhancement in the COP and does reduce the compressor work of the AAC system. The comparison between Al₂O₃-SiO₂/PAG, Al₂O₃/PAG and SiO₂/PAG nanolubricant demonstrates that Al₂O₃-SiO₂/PAG, has better performance in term of compressor work reduction and COP enhancement at an average of 28.7 % and 31.64 %, respectively. At last, it was recommended to use the Al₂O₃-SiO₂/PAG nanolubricant for application in AAC system.

1. Introduction

The air conditioning system is now a necessary component of the living population. The air conditioning system in the car is called Automotive Air Conditioning (AAC). This system has become essential and must be installed in commercial vehicles. The AAC system uses much energy from the engine. In a past study by Rugh et al. [1], AAC has used up to 50 % of the total engine power and contributes to the release of NO_x and CO gas up to 80 % and 70%. Car technologies and AAC system are improving throughout the years, and the power used up by the AAC system inside the modern car may decrease by 10 % to 20 % of the total energy of a vehicle. In the future, fossil fuel will be depleted, and electric vehicles will use alternately; hence the efficiency of the AAC system should also be improved to meet the challenges ahead.

So far, researchers have tried various methods to improve the AAC system. At present, nanotechnology is used in lubricating oils of the compressors found in Vapour Compression Refrigeration System (VCRS) to enhance tribology and antiwear features, heat transfer enhancements, and the refinement of refrigerant-oil mixture characteristic [2-4]. Nanoparticles can be added to the base



lubricant to produce nanolubricant. Along with the rapid development of technology, nanolubricant technology has also evolved from time to time. The first generation of nanolubricant is more focused on only one type of nanoparticles, of which only one type of nanoparticles is mixed into the base lubricant. Sharif et al. [5] investigate the effect of Al_2O_3 nanoparticles additives into PAG lubricant. The results from the thermo-physical study show that the enhancement of thermal conductivity by up to 4 % at a volume concentration of 1.0 %. However, the viscosity of the Al_2O_3 /PAG nanolubricant sharply rose up to 700 % at 0.4 % volume concentration which limiting the potential of nanolubricant. This is because the lubricant that has high viscosity tends to draw more pumping power despite having more better antifriction properties [6]. The same nanolubricant, Al_2O_3 /PAG was tested in an AAC experiment done by Redhwan et al [7]. In the experiment, optimum Al_2O_3 /PAG nanolubricant with 0.010 % volume concentration proved to provide the best performance of the AAC system. The maximum recorded COP enhancement for Al_2O_3 /PAG nanolubricant is 31 % with an average enhancement of 28 %. A recent study has investigated the thermos-physical properties of SiO_2 /PAG nanolubricant [8]. The results show the increment of thermal conductivities for 4.8 % at 1.5 % volume concentration. A lower enhancement in thermal conductivities of SiO_2 /PAG compared to Al_2O_3 /PAG is expected due to lower thermal conductivity exhibit by the SiO_2 nanoparticles. However, the increment in viscosity for SiO_2 /PAG nanolubricant are only 500 % at a volume concentration of 1.5 %, which lower compared to Al_2O_3 /PAG. Later, the effectiveness of SiO_2 /PAG nanolubricant is tested in an AAC experiment employing the nanolubricant [9]. The best coefficient of performance (COP) for AAC system with SiO_2 /PAG nanolubricant are at a volume concentration of 0.05 %. The maximum COP enhancement for SiO_2 /PAG nanolubricant is recorded up to 24 % with an average enhancement of 10.5 % while the compressor work reduced up to 5 %.

The second generation of nanolubricant is called the composite nanolubricant or composite nanolubricant. Generally, composite nanolubricant comprised a mixture of two or more types of nanoparticles added to the base lubricant. The composite nanolubricant usually have better stability, better heat transfer, and improve tribology characteristic. However, that depends on the ratio of the nanoparticles inside the lubricant. Nadia et al. [10] have studied the thermo-physical properties of composite nanolubricant. Al_2O_3 and SiO_2 nanoparticles are mixed into the PAG base lubricant to form Al_2O_3 - SiO_2 /PAG nanolubricant. The Al_2O_3 - SiO_2 /PAG nanolubricant indeed have better thermo-physical properties with the enhancement of thermal conductivity and viscosity up to 2.4 % and 9.71 % respectively at a volume concentration of 0.1 %. The improvements in thermal conductivity are better compared to the single nanolubricant display by Al_2O_3 /PAG and SiO_2 /PAG with only a small increment in viscosity. In other words, a higher volume concentration of composite nanolubricant can be used in AAC system because of the minimal increase in viscosity compared to single nanolubricant. The composite nanolubricant also have a higher zeta potential value, which corresponds to greater stability with minimal sedimentation. In another study, the Al_2O_3 - SiO_2 /PAG composite nanolubricant have a high coefficient of friction (COF) and a better anti-wear properties which is 5 % and 12 % respectively [11]. These will helps to reduce to mechanical friction inside the compressor thus helps to lengthen the service life of the AAC compressor. Until now, there has been no experiment involving Al_2O_3 - SiO_2 /PAG users in the AAC system.

The goal of this study to develops a more rigorous understanding of the effect of different nanolubricant inside a vapour compression refrigeration system. An experimental study will be conducted involving Al_2O_3 - SiO_2 /PAG inside the AAC system. The experimental result involving the energy performance of AAC system will be presented in term of COP and compressor work value. Then, the performance of AAC system using nanolubricant in the previous study will be compared with the current experimental results.

2. Methodology

2.1. Preparation of the nanolubricant (Al_2O_3 - SiO_2 /PAG)

The working fluid for AAC system used in this experiment using R134a refrigerant and PAG lubricant as the compressor lubricant. The excellent performance of AAC system requires composite

nanolubricant with a stable, significant enhancement in thermal conductivity with low increment in viscosity and better tribology characteristic properties. For this reason, Al₂O₃-SiO₂/PAG with a ratio of 60:40 and a volume concentration of 0.015 % are prepared for this experiment. The thermo-physical properties and stability of the Al₂O₃-SiO₂/PAG composite nanolubricant have been studied in previous research [10, 12, 13]. The tribology characteristic of Al₂O₃-SiO₂/PAG is also have been studied in past research [11]. In the study, Al₂O₃ with 13 nm in size and 99.8 % purity are used and procured. For SiO₂ (amorphous) nanoparticles, were used and procured also with 99.9 % purity with an average size of 30 nm. The properties of Al₂O₃-SiO₂/PAG and PAG 46 lubricant at atmospheric pressure are shown in Table 1.

Table 1. Properties of Al₂O₃-SiO₂/PAG (at $\phi = 0.015\%$) and PAG 46.

Properties	Al ₂ O ₃ -SiO ₂ /PAG	PAG 46
Thermal Conductivity (W m ⁻¹ K ⁻¹) @ 313 K	0.1482	0.145
Kinematic viscosity, (cSt) @ 313 K	42	41.4

The present composite nanolubricant was prepared by a two-step method. The intended volume concentration of nanolubricant in the present study was calculated using equation (1) [14]. The volume concentration in percentage (vol %) are equal to the ratio of the volume of nanoparticle (v_p) and the total volume of solution; which is equal to the addition of the volume of nanoparticle and the volume of lubricant (v_l).

$$\phi = \left[\frac{v_p}{v_p + v_l} \right] \times 100 \quad (1)$$

The initial mixing process is done by using a magnetic stirrer. The required mass of the Al₂O₃ and SiO₂ nanoparticles to be dispersed in lubricant was precisely measured utilizing a high accuracy electronic balance. The mixture then is subjected to ultrasonic homogenization for two hour to ensure good dispersions of nanolubricant. The detailed steps of preparation was explained by in previous research [10, 12, 13, 15, 16].

2.2. AAC Experimental Setup

Figure 1 shows the basic schematic diagram of AAC experimental test setup. The AAC test setup was developed from the original components of an automotive air conditioning system [2]. The refrigeration system was the AAC system that comes out from the typical use compact car and it was utilized from a 660 cc engine capacity compact car specification. The refrigeration capacity of the AAC in the experiment is the requirement of the normal compact car in Malaysia, which is about 1.2 hp[17]. Similar trend of cooling capacity that was also observed by other researcher [18]. The experimental setup can be classified into four main major parts. The first part was the refrigeration system. The major components of a standard AAC system include compressor, condenser, evaporator, expansion valve and the piping system. Then the second part is the driver and control system, where it utilized an electrical motor and an inverter frequency controller. The compressor pulley is driven by a 2.2 kW, 3-phase electrical motor and integrated with a frequency inverter. The use of the frequency inverter to control and vary the rotational speed of the motor is. Here, the speed is set between 900 and 2100 revolutions per minute (RPM). Throughout the experiment, the compressor was run continuously without the cycling system. The third part is the water bath system for evaporators and the piping systems.

Lastly, the final part covered the whole experimental setup was instrumentation and data logger of the AAC system. Temperature indicators, pressure gauges and digital power analyser also instrumented properly in the AAC system. The temperature reading at 9 different locations was carried out using a calibrated K-type thermocouple in accordance according with ANSI/ASHRAE (2001) [19]. Seven (7) different locations were installed with the thermocouple in the AAC system pipeline and at specific

locations of the inlet and outlet for each main component. The K-type thermocouple is 0.3 mm in diameter and designed for temperature ranges between 233.15 and 648.15 K with tolerance of ± 1.5 K. All temperature readings and water flow rate measurements were monitored and recorded through a data logger module. Evaporator and condenser pressures were measured using calibrated pressure gauges and recorded manually. The power consumption of the AAC system was monitored and measured using power analysers. To confirm all the measurement devices in this study work perfectly, the calibration method was applied. The initial refrigerant charge was measured using a weight scale in gram. About 160 grams of R134a refrigerant is charged into the AAC system. Finally, the room temperature and air humidity were monitored and controlled between 297.65 and 298.65 K and at 45 and 65 %, respectively throughout the experimental work.

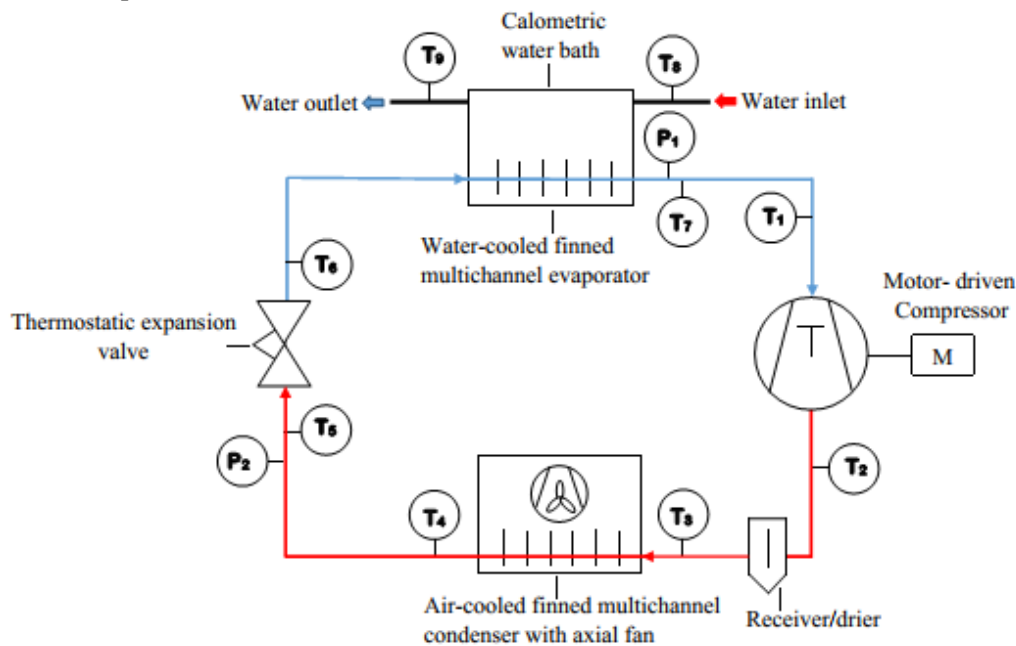


Figure 1. The schematic diagram of automotive air conditioning (AAC) system.

2.3. Experimental Setup – Performance Analysis

In the AAC system test setup, the vapour-compression refrigeration cycle was considered and assumed that the cycle was without pressure drop in the condenser, evaporator and in all refrigerant pipe lines. Then, the condensing and evaporating pressures were assumed to be equivalent to the discharged and suction pressures measured by the pressure gauge. Also, the system was expected to achieve a steady operating condition after 20 minutes of running. In addition, the kinetic and potential energy changes were assumed to be negligible. Temperatures and pressures recorded at the particular locations are very important for determination of the heat absorb, the compressor work and the COP of the AAC system. Both temperature and pressure were used simultaneously to determine the enthalpy value. Later, the following parameters related to COP were identified. In this experiment, 5 sets of data for temperatures and pressures were collected to indicate 5 compressor speed ranging from 900 to 2100 rpm. Each set of data was repeated three times to ensure its reliability and consistency. The temperatures and pressures were recorded for 10 minutes, just after 20 minutes of running the AAC system, which is expected to be in a steady-state condition according to SAE J2765 standard [20]. Both temperature and pressure were required to determine the enthalpy using the properties table at each point of interest. Then, the final average enthalpy value was obtained from the repeated data. From the enthalpy value, the heat absorb (q_L), the compressor work (w_m) and coefficient of performance (COP) could be determined using equations (2), (3), and (4) respectively [9].

$$q_L = h_6 - h_7 \quad (2)$$

Where $h_5 = h_6$ (Isentropic process)

$$w_{in} = h_2 - h_1 \quad (3)$$

$$COP = \frac{q_L}{w_{in}} = \frac{h_6 - h_7}{h_2 - h_1} \quad (4)$$

2.4 Consistency Analysis

The summary for the uncertainties of the experimental parameters are shown in Table 2. The experimental involving the parameters of the water flow meter, tachometer, weighing scale, pressure gauge and K-type thermocouples. The data from all parameter that have been collected must be calculated their measurement error using percent of relative standard error (RSE) given by the Eq. (5) [9].

Table 2. The summary for the uncertainties of the experimental parameters.

Parameters	Full Scale	Uncertainty
Pressure gauge, psi	0 - 200	± 0.1
Water flow meter, LPM	0 - 100	± 0.1
K-type thermocouples, K	233 to 648	± 1.5
Tachometer, RPM	0 - 20,000	± 2
Weighing scale, kg	0 - 25	± 0.001

$$RSE = \frac{S_{err}}{\bar{X}} \times 100\% \text{ where, } S_{err} = \frac{\sigma}{\sqrt{n}} \quad (5)$$

3. Results and discussion

3.1. AAC performance with Al_2O_3 - SiO_2 /PAG composite nanolubricant

Figure 2 shows the graph of compressor work comparison between PAG and Al_2O_3 - SiO_2 /PAG against the compressor speed. The graph shows that there has been a steady increase in compressor work as the compressor speed increases for the same condition. As the compressor speed increases, the compressor discharge temperature and pressure also increase. As a result, the enthalpy difference at the compressor also increases which is the compressor work increases. It is also very clear from Figure 2 that the Al_2O_3 - SiO_2 /PAG composite nanolubricant have a lower compressor work at all range of compressor speed. Several factors in tribology are known to affect the reduction of the compressor work in the AAC compressor system. The Al_2O_3 - SiO_2 /PAG indeed have a better tribology characteristic compare to the base lubricant as reported by Nadia et al [11], thus contributing to the decline of compressor work.

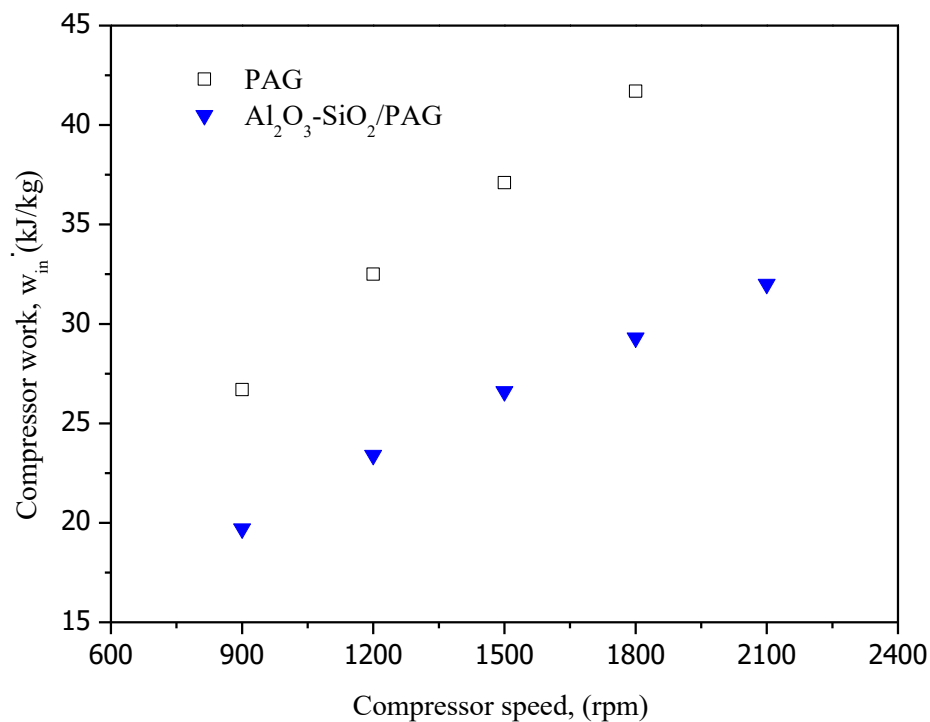


Figure 2. The graph of indicated AAC compressor work against various compressor speed.

The effect of compressor speed on the coefficient of performance (COP) is illustrated in Figure 3. The graph shows that the COP decreases as the compressor speed increases. The COP is mainly the result of ratio between heat absorb and compressor work. For lower compressor speed, the compressor work also have a lower value as shown in Figure 2. This causes the ratio between of heat absorb and compressor work (COP) to increase. As the compressor speed increase, the compressor work is also increasing and as a result, the ratio attains low values at higher speed. It is very clear from Figure 3 that the AAC system with $Al_2O_3-SiO_2/PAG$ have a greater COP than the AAC system with base lubricant PAG. The finding is consistent with the findings of past studies [7, 21, 22], which the COP of VCRS system that use nanolubricant have higher performance compared to the system with original lubricant.

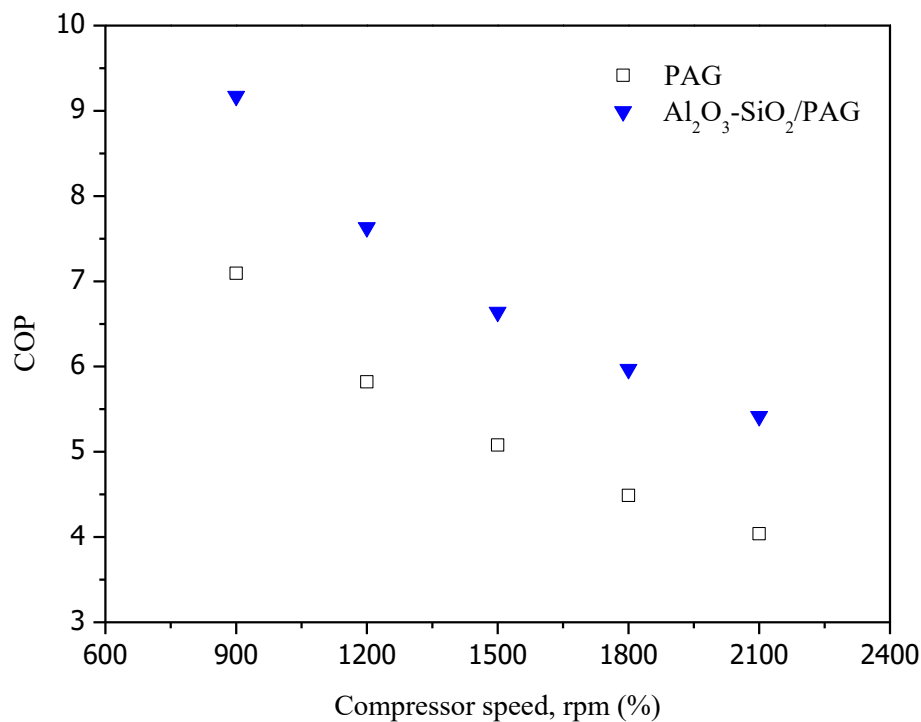


Figure 3. The graph of AAC COP against various compressor speed.

3.2. AAC performance comparison with different nanolubricant

Researchers have studied the role of additives and the effects of various lubricants on the performance of VCRS [23]. These studies have proved that various types of compressor oils and additives also have differentiate in terms of performance as well as tribology. Previous studies from Sharif et al. [22] and Redhwan et al. [7] has been dealt with the effectiveness of nanolubricant in the AAC system using only one type of nanoparticles namely SiO₂ and Al₂O₃ respectively. Both studies use the same experimental setup and base lubricant. Therefore, it is very reasonable to compare the results of the present study with the previous study.

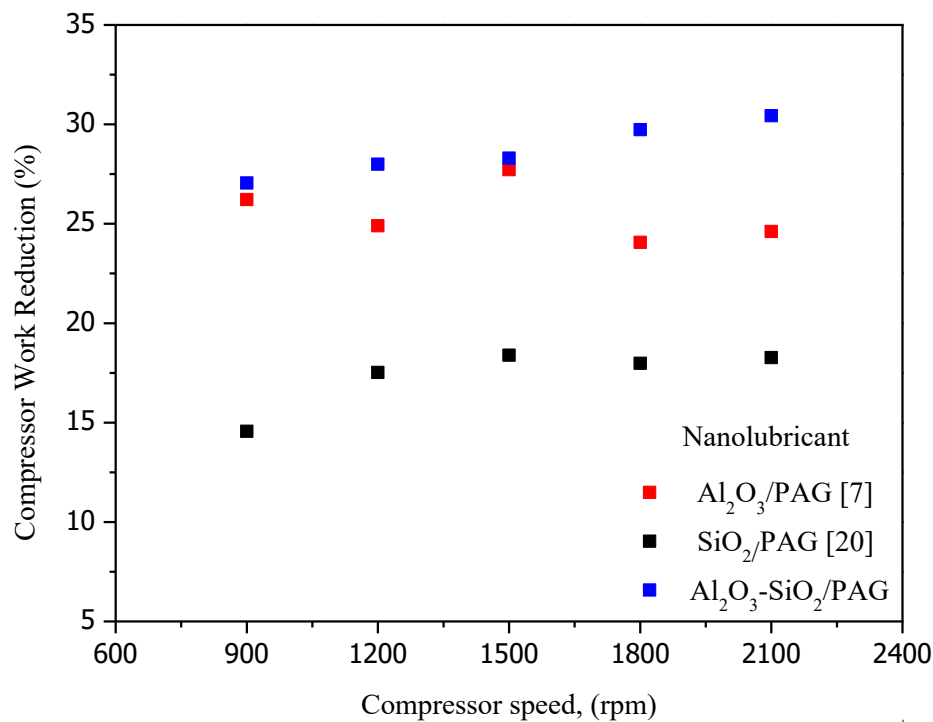


Figure 4. The graph of indicated AAC compressor work against various compressor speed for different types of nanolubricant.

Figure 4 illustrates the compressor work reduction in term of percentages for different types of nanolubricant against compressor speed. What is interesting in this graph is the high reduction of compressor work of AAC system are recorded when the Al₂O₃-SiO₂/PAG nanolubricant are used in the system. High compressor work reduction in AAC system caused by a better tribology properties especially in coefficient of friction and antiwear properties exhibit by the composite nanolubricant [11]. Figure 5 show the COP enhancement in term of percentages for different types of nanolubricant against compressor speed. The relationship between lubricant thermo-physical properties and VCRS performance has been widely investigated in past research [3, 24, 25]. Recent research has revealed that Al₂O₃-SiO₂/PAG have better thermo-physical properties compared to its individual single nanolubricant. This better thermo-physical properties in lubricant prove to have a positive effect on the AAC heat absorb and cooling capacity. Since COP is the ratio of heat absorb and compressor work, the increase of heat absorb and reduction in compressor work as shown in Figure 4 helps in the increment of COP.

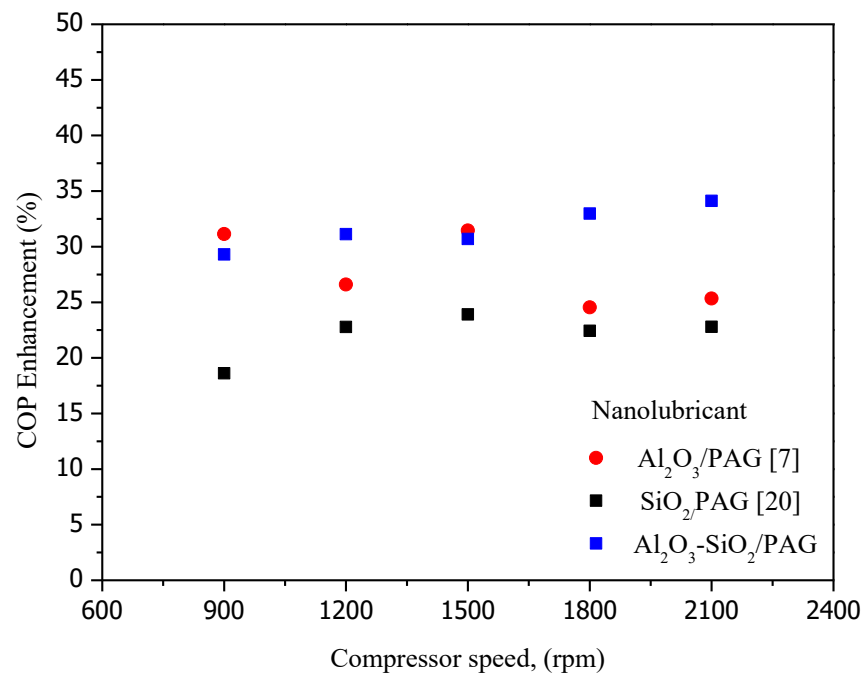


Figure 5. The graph of AAC COP against various compressor speed for different types of nanolubricant.

4. Conclusion

An experimental study using Al₂O₃-SiO₂/PAG in AAC system test setup is used to explore the relationship between the enhancements in thermo-physical properties of the composite nanolubricant affect the AAC system performance. The compressor work and COP of the AAC system against different compressor speed were discussed. It was found that:

- The AAC system with Al₂O₃-SiO₂/PAG composite nanolubricant has a lower compressor work at all range of compressor speed.
- The AAC system with Al₂O₃-SiO₂/PAG has a greater COP than the AAC system with base lubricant PAG.
- The comparison between Al₂O₃-SiO₂/PAG, Al₂O₃/PAG and SiO₂/PAG nanolubricant demonstrates that Al₂O₃-SiO₂/PAG, has better performance in term of compressor work reduction and COP enhancement at an average of 28.7 % and 31.64 %, respectively.

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