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RESEARCH ARTICLE

Investigation of different compressor speeds to improve the performance of residential air conditioning system using hybrid nanolubricant

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ABSTRACT - Nanoparticles dispersed into lubricants improve the performance of residential air conditioning (RAC) systems. Due to the addictive nature of nanoparticles, friction losses are reduced, and heat transfer is enhanced, leading to a significant increase in the overall efficiency of the RAC system. This study aimed to investigate different compressor speeds utilising hybrid nanolubricant to improve the performance of RAC. A two-step method was used to prepare TiO_2 and SiO_2 nanoparticles dispersed into polyvinyl ether (PVE) lubricant at a volume concentration of 0.008%. R32 refrigerant was formulated with PVE lubricant at a refrigerant charge of 360 g and compressor speeds of 2520, 2760, and 3000 rpm. The dispersion of both nanoparticles into PVE lubricant at a binary ratio of 50:50 showed excellent stability. The results of the experimental study showed that the coefficient of performance (COP) at each compressor speed of 2520, 2760, and 3000 rpm increased by 8.04%, 4.51%, and 2.46%, respectively. Then, the compressor work decreased by 8.05%, 6.30%, and 4.53%, respectively, decreasing maximum power consumption by 3.56% at a compressor speed of 2520 rpm. Increasing COP at low speeds has implications for the compressor work, which causes the mass flow rate to decrease. At the same time, the refrigerant effect increases, and finally, the COP increases. It is concluded that utilising hybrid nanolubricant in the refrigeration system can improve the overall performance of RAC.

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1. INTRODUCTION

The RAC demand for the Asian region is projected to increase by 40% by 2040 and is estimated to grow by 1.54% per year [1]. According to the Montreal Protocol criteria, innovative mass production is needed to meet market demand, such as energy-efficient, low-emission, and environmentally friendly RAC systems [2, 3]. A typical innovation is to improve RAC performance. When COP increases indirectly, the compressor work decreases, decreasing power consumption. Hussein [4] reported a positive trend in increasing COP, which can be achieved by dispersing nanoparticles into lubricants. In their experiments, it was shown that the addictive nature of nanolubricants maximises compressor work by reducing friction on sliding surfaces, and as a result, the compressor work decreases by 13.3%. In this case, the refrigerant also has the same contribution, such as the R134a refrigerant paired with Al_2O_3/POE (Polyol ester), SiO_2/PAG (Polyalkylene Glycol), and TiO_2/POE nanolubricants. The results show a significant increase in COP by 4.4%, 24%, and 4.70% [5, 6]. This trend is because nanolubricant can reduce heat, thereby increasing heat transfer efficiency in the evaporator and condenser. On the other hand, pure lubricants, nanolubricants, and refrigerants will mix some parts in the same phase, for example, during evaporation, because both are in the liquid phase. If the oil is not compatible with the refrigerant, the two will separate even though they are in the same phase, which causes the oil not to return to the compressor and risks increasing compressor work. Therefore, compatibility between refrigerant and lubricant is essential, as is the case with R32/PVE and R32/POE, which have been declared compatible. As a result, the COP increases by 39.2% and 32.26% respectively [7].

Nanoparticle dispersion into lubricants is one method used to improve system performance. Evaluating nanolubricant stabilisation is needed as a fundamental step in utilising nanoparticles. In the literature, nanolubricants are generally prepared using one-step or two-step methods. The one-step method is a simple process of dispersing nanoparticles with fluids. Studies of this method, such as nanoparticle powder tests, provide optimal results, suspended nanoparticles, and short synthesis, which are economical. The two-step method was developed based on the need for non-particle characterization, which has high efficiency. Stabilization and agglomeration factors are developed to maximize quality. Therefore, one observation of nanolubricant stabilization that can be used is to look at its zeta potential. Safril, et al. [8] stated that nanoparticles with an equilibrium correlation with lubricants show better nanolubricant stability. This condition is due to minimal clumping and aggregation, which suggests low agglomeration because the colloidal nature attracts each other. As a result, the higher the zeta potential value, the better the stabilisation [9, 10]. Evaluation of nanolubricant

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stability is interpreted as an initial step before being applied to a refrigeration system. This step provides better consequences before the experiment. Previous studies have revealed that nanolubricants applied to refrigeration systems have a positive impact. Nanolubricants improve the lubrication system in the compressor. This is because nanolubricants have good thermal conductivity compared to pure lubricants, thereby increasing lubrication efficiency and reducing friction and wear. Chen, et al. [11] and Dhanola and Garg [12] conducted a study on this. The results showed that adding a volume concentration of nanoparticles to pure lubricants can increase thermal conductivity and dynamic viscosity. When the performance of both increases, the compressor work decreases, and eventually, the COP increases.

Mono and hybrid nanolubricants have characteristics that improve the lubrication system in compressors. The nanolubricants have characteristics that improve the lubrication system in compressors. In the RAC system, diamond nanoparticles are dispersed into POE lubricants operated with R32 refrigerant. The results showed high efficiency in the refrigeration system [13]. A similar nanolubricant was observed by Aljuwayhel, et al. [14] using diamond/POE operated with R410a. The COP increased by 8%, and power consumption decreased by 3%. This result shows that mono nanolubricants positively impact the refrigeration system. On the other hand, hybrid nanolubricants combine two nanoparticles dispersed into a pure lubricant. Saravanan [15] reported that Al_2O_3-TiO_2/POE hybrid nanolubricant with a binary ratio of 50:50. The result was an increase in COP of 11.89% and a decrease in compressor performance of 12.29%. In line with Kumar, et al. [16], they investigated TiO_2-SiO_2/POE hybrid nanolubricant with a binary ratio of 25:75. The result was an increase in system performance with a decrease in power consumption of up to 8%. The efficiency of hybrid nanolubricants showed positive results. Even in small amounts, dispersing TiO_2 and SiO_2 nanoparticles into pure lubricants can increase COP. This result is because the nanoparticle additive has better thermal conductivity than pure lubricants [17]. During the refrigerant compression process, the compressor produces heat. When the heat is not released into the environment properly, it causes an increase in pressure and compressor work. Zawawi, et al. [18] revealed that hybrid nanolubricants have good thermal conductivity compared to pure lubricants so that heat from the compression process is released faster, and compressor work is reduced. Consequently, power consumption is reduced linearly. In the refrigeration system, hybrid nanolubricants help heat absorb in the evaporator and release heat in the condenser. When this scheme runs, the result is more efficient heat transfer, and then the refrigeration effect increases without excessive compressor work.

Compressor speed has a significant effect on the performance of the refrigeration system. This condition was proven through experimental studies on AAC systems, with speed variations between 900 and 2100 rpm and SiO_2/PAG with a volume concentration of 0.05 - 0.7%. The results showed that at a volume concentration of 0.05%, there was an increase in COP of 21%, a decrease in compressor work of 16.5%, and a decrease in power consumption of 4% [19]. In this case, the volume concentration affects the COP value, where mono nanolubricant can increase COP and, at the same time, reduce compressor work. Further investigation was undertaken with the same system and speed variations, with a binary ratio of 60:40 for Al_2O_3-SiO_2/PAG hybrid nanolubricant with a volume concentration of 0.005 - 0.06%. The results showed that the COP trend was higher at low compressor speeds (900 rpm), and low volume concentration dominated the increase in COP. This result shows that nanolubricants with different compressor speed variables and lower percent of volume concentrations show satisfactory results.

The study of hybrid nanolubricant in RAC systems is still limited in the literature. This condition is because the RAC system generally uses a fixed-speed compressor or compressor speed that adjusts the cooling capacity. Therefore, researchers have conducted many observations in AAC rather than the RAC system, especially on the compressor speed variable. The compressor speed is fascinating to investigate because the hybrid nanolubricant character in the RAC system has different behaviour towards COP. Observation of this variable is novel, especially the TiO_2-SiO_2/PVE hybrid nanolubricant, which is used to investigate the performance of the RAC system. Since low concentration volume shows better results, 0.008% concentration volume was utilised in this study. A two-step method is used to prepare hybrid nanolubricants with a binary ratio of 50:50, where the 50:50 ratio allows for an even representation of both types of nanoparticles, and an even distribution can reveal ideal trends or patterns. Experimental studies of RAC system performance are carried out with different compressor speeds, and the final results, such as COP, compressor work, and power consumption, are investigated.

2. MATERIALS AND METHODS

2.1 Preparation of Hybrid nanolubricant

TiO_2 and SiO_2 nanoparticles were dispersed into polyvinyl ether (PVE) lubricant, which had diameters of 50 and 30 nm, respectively, with densities of 4230 and 2220 kg/m^3. TiO_2 nanoparticles were procured through HWNANO, a leading supplier in Guangzhou, China, by Hongwu International Group Ltd. SiO_2 nanoparticles were obtained from DKNANO, a company specialising in scientific and technological advancement in Beijing, China. Both nanoparticles had a high purity of 99.9%. Meanwhile, PVE or FVC68D has a viscosity of 68. This lubricant was used for the rotary compressor with a capacity of 300 ml, which was obtained from Idemitsu Kosan Co., Ltd. PVE lubricant has the following specifications: dynamic viscosity at 40 ºC is 62.58 mPa and density at 15 ºC is 0.94 g/cm^3 [20]. R32 refrigerant was paired with PVE, which was declared compatible [21]. Refrigerant R32 (HFC-32) with the chemical formula CH_2F_2 and molar mass of 52.024 is used with ASHRAE standard 34 and International Standard ISO 817 category 2L (Slightly flammable)

[22, 23]. Table 1 shows the specifications of the materials used in this study, such as nanoparticles, lubricants, and refrigerants.

Table 1. Material specification of nanoparticle, lubricant, and refrigerant

Properties	Nanoparticle		PVE	R32
	TiO_2	SiO_2		
Molecular mass, [g/mol]	70.97	60.08	-	-
Average particle diameter, [nm]	30-50	15	-	-
Density, [kg/m^3]	4230	2220		
Specific heat, [J/kgK]	692	745	-	-
Viscosity, [mm^2/s @ 40 °C]	-	-	66.57	-
Dynamic Viscosity, [mPa @ 40 ℃]	-	-	62.58	-
Density, [g/cm^3 @ 15 °C]	-	-	0.94	-
Flashpoint, [°F] ASTM D92	-	-	>356	-
Molecular weight [g/mol]	-	-	-	52.024
Boiling point [°C]	-	-	-	-51.65
Vapor pressure, [psia @ 25 ℃]	-	-	-	245.06
Vapor density [kg/m^3 @ 25 ºC]	-	-	-	424

A two-step method was used to prepare TiO_2-SiO_2/PVE hybrid nanolubricant with a volume concentration of 0.008%. The hybrid nanolubricant was prepared separately for a 50:50 binary ratio. 50% of TiO_2 nanoparticles were mixed into 150 ml lubricant, and the remaining 50% for SiO_2/PVE nanoparticles. Equation (1) was used to calculate the volume concentration of nanoparticles.

$$\phi = \left(\frac{m_p}{\rho_p} \Big/ \frac{m_p}{\rho_p} + \frac{m_l}{\rho_l} \right) \times 100\% \tag{1}$$

where, ϕ is the volume concentration, m_p and ρ_p are the mass and density, and m_l and ρ_l are the mass and density of PVE lubricant.

The mixing stage was carried out after a weighing session, where the nanolubricant was connected to a beaker and stirred using a magnetic stirrer for 0.5 hours. The homogenisation process was the final preparation stage, and the Fischerbrand FB15051 ultrasonic water bath was used in this session. A constant frequency of 37 Hz with an average power of 80 W was considered in this preparation. Homogenisation was carried out for 7 hours because it has better stability efficiency. The stability of hybrid nanolubricant is influenced by the distribution of nanoparticles dispersed into the PVE lubricant. When the sonication time is insufficient, the hybrid nanolubricant has a high level of agglomeration. This trend is due to the gravitational force acting inside the tube, which causes the nanoparticles to fall to the bottom area of the tube. Therefore, it is concluded that the stability of hybrid nanolubricant is influenced by the sonication duration.

Zeta potential is used in this study to observe the stability of TiO_2-SiO_2/PVE hybrid nanolubricant quantitatively. Zeta potential Litesizer 500, made by Anton Paar, can measure particles in the range of 0.3 nm - 10 μm (particle size) and 3.8 nm - 100 μm (zeta potential) according to its specifications. Observations such as colloidal incorporation, transmittance, velocity index, and changes in the impact layer are observed in a stable state. When the zeta potential value of the suspension is low or almost zero, a flocculation process occurs in the hybrid nanolubricant sample so that clumping occurs. This condition is due to the nature of colloids that try to attract each other. Therefore, this observation is expected to produce a zeta potential value greater than 60 mV, a category of excellent stability [24]. For clarity, the categorization of zeta potential values is shown in Table 2.

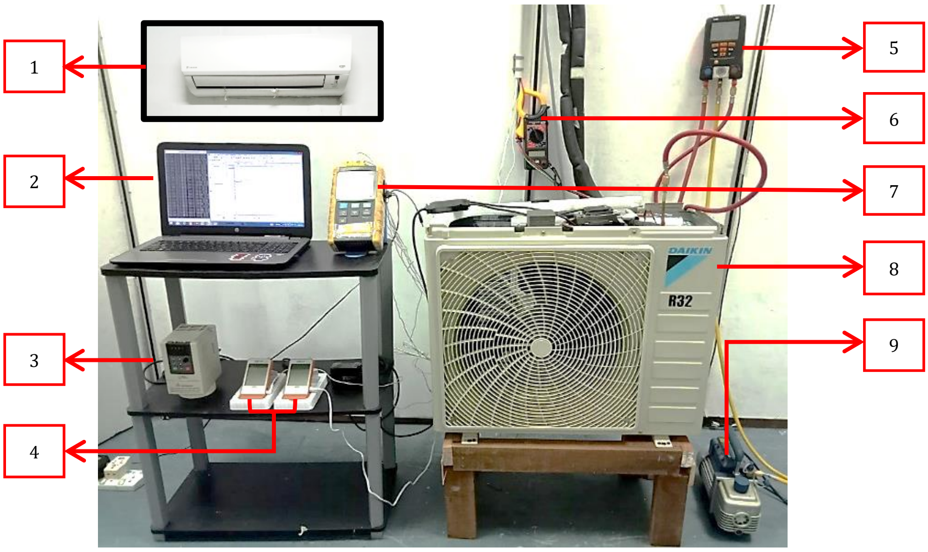
Table 2. Zeta potential of stability category [25, 26]

Zeta Potential (mV)	Stability Category
0	Unstable
15	Some stability
30	Moderate stability
45	Good stability
60	Excellent stability

2.2 Test-Rig and Apparatus Commissioning

The RAC system is obtained from Daikin – Malaysia Sdn Bhd with the FTV-P series for indoor unit code FTA-28PBV1MF and outdoor unit RV28PBV1M. The experimental equipment used in this study is shown in Figure 1. The test-rig design between the indoor and outdoor units is back-to-back with standard operational power of 3.86 A and 0.865 kW. Copper pipes connect the indoor and outdoor installations with dimensions of 6.35 and 9.52 mm, respectively. The 3.86 A and 0.865 kW are the default input power and current. The test equipment in the thermal control room (TCR) and RAC system refers to the ISO5151:2010 standard and the Malaysian standard MS1525:2014.

As an initial step in the operation of the RAC system, operational procedures are carried out following applicable provisions. For example, using the manufacturer's lubrication FW50S paired with refrigerant R32 and repeated three times to ensure the RAC system functions appropriately. At the same time, each test equipment was checked to ensure current leakage in the circuit, gas leakage in the pipe, and related components. After the test equipment was functioning correctly, the lubricant and gas in the RAC system were removed. The SP-888 flushing unit is used to flush the RAC system, carried out 2-3 times. A vacuum pump was used for 30 to 60 minutes to ensure that both evacuations were successful. This vacuum process also serves to verify leaks in the piping system. When the manifold indicator screen shows unchanged pressure results, the system is declared in good condition because there is no leak. Then, the system is declared ready, and PVE/R32 is operated first before the hybrid nanolubricant investigation.



1. Indoor unit, 2. Laptop, 3. VFD 4. Temperature analyser (data logger), 5. Pressure gauge, 6. Clamp meter, 7. Data logger, 8. Outdoor unit, 9. Vacuum pump

Figure 1. Experimental test-rig of RAC system

Figure 2 is a schematic diagram of the RAC system used during the experiment. The power control system uses a variable frequency drive (VFD), and the electrical energy capacity is calculated using a power analyzer. Meanwhile, the temperature control system combines a humidifier and a heater to control the air entering the indoor and outdoor units. The standard temperature T1 was used throughout the test, where the indoor and outdoor temperatures were maintained according to the recommendations, as shown in Table 3. These recommendations are stated in the ISO5151 and Malaysian MS1525 standards [27, 28]. T1 is intended for various temperate climate conditions. The supporting equipment in this investigation, such as thermocouples, have been calibrated at room temperature, boiling point, and freezing point of water and utilising mercury thermometers as validation [29]. Meanwhile, the certified manufacturer calibrated the flow meter, pressure gauge, and electrical analyser.

Table 3. Recommended T1- standard ISO5151:2010 and MS 1525:2014 [27, 28]

Condition	Recommended of Air Entering Indoor	Recommended of Air Entering Outdoor
Dry bulb	27 ℃	33.3 ℃
Wet bulb	19 ℃	27.2 ℃

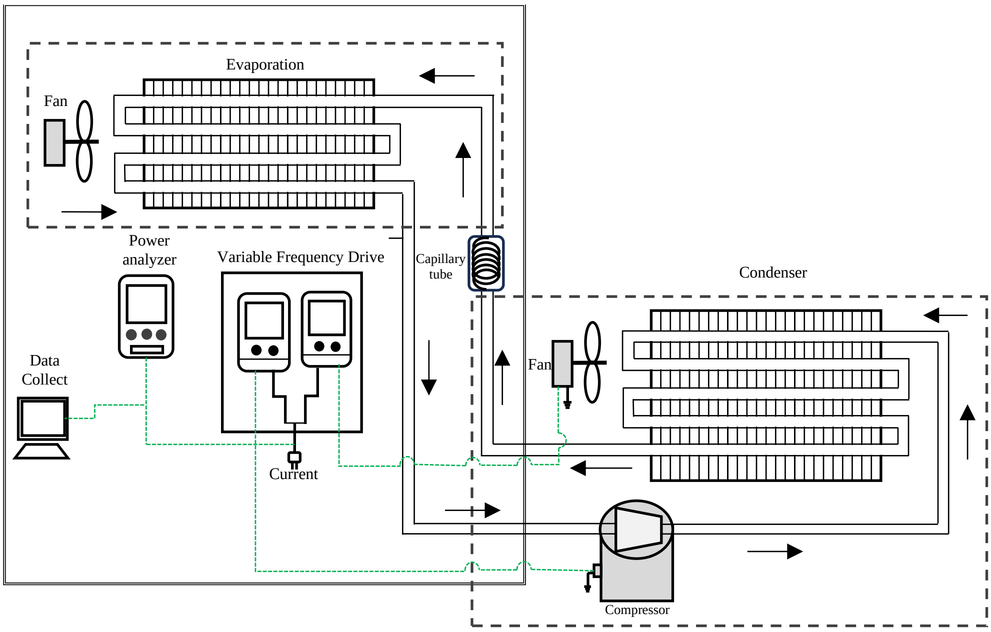


Figure 2. Schematic diagram of the RAC system

2.3 Procedure of Experimental

This study used R32 with a refrigerant charge of 360 g. The standard T1 was used during the experiment, which recommended 27 °C for entering air and 33.3 °C for outdoor ambient temperature. The RAC system was run continuously for 60 minutes in the experimental process. At the same time, data collection was carried out to verify the steady-state condition to obtain stable conditions. After reaching stable conditions, data collection was carried out for 30 minutes, and the results were analysed and compared between PVE/R32 and hybrid nanolubricant. The current vapor-compression refrigeration (VCRs) system cycle for R32 refrigerant is illustrated as a p-h diagram in Figure 3.

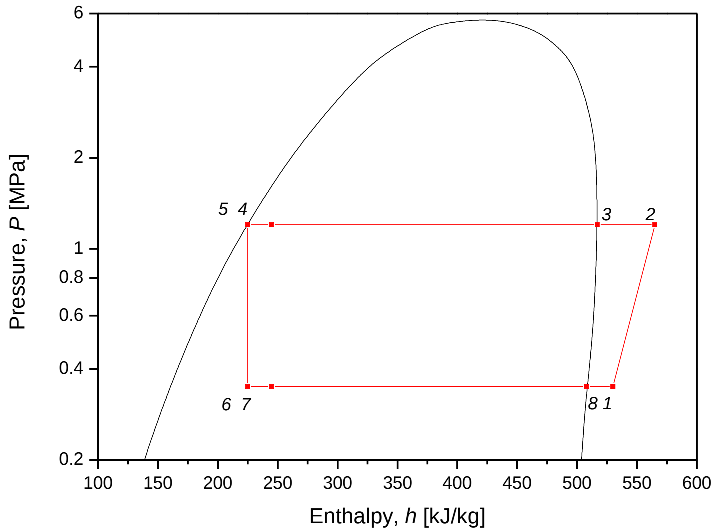


Figure 3. *P-h* diagram for the R32 at VCRs condition

Data collection was conducted throughout the experiment to be calculated, such as h_1, h_2, and h_5, respectively, for compressor suction enthalpy, compressor exhaust enthalpy, and evaporator inlet enthalpy. PROVA 6830A detection device was used for power consumption data collection, and a variable frequency drive (VFD) was used to control the compressor speed. Furthermore, data analysis was arranged using a Ph diagram for R32 refrigerant based on the vapour compression refrigeration (VCRs) system. Equation (2) was used to assess the refrigeration effect, and Eq. (3) was used to evaluate the compressor's work. COP evaluation in the VCRs cycle used Eq. (4). In addition, it was assumed that ($h_5 = h_6$) because it has the same enthalpy value.

$$q_L = h_1 - h_6 \tag{2}$$

$$W_{in} = h_2 - h_1 \tag{3}$$

$$COP = \frac{q_L}{W_{in}} \tag{4}$$

2.4 Uncertainty and Consistency Analysis

Table 4 shows the equipment's uncertainties, which measure the quantity obtained from the experiment. Testo 550 is used to measure pressure with the measurement range from -0.1 to 6 MPa, and then the uncertainty value is ±0.5%. Thermocouple, K-type is measured at -50 to 250 °C, and the uncertainty is ±0.1 °C. The power analyser's and clamp's uncertainty values on mass flow rate are ±0.01 kW and ±2.9 mL/min, respectively.

Table 4. Instrumentation and uncertainty measurements

Equipment	Measuring Range	Uncertainty
Pressure gauge, Testo 550 type	-0.1 to 6 MPa	±0.5%
Thermocouple, K-type	-50 to 250 °C	±0.1 °C
Power analyser, PROVA 6830A	1 to 10 kW	±0.01 kW
Clamp-on mass flowrate, Keyence FD-XS8	0 to 3000	±2.9 mL/min

The measurement error calculation based on the percentage of relative standard error (RSE) was used in this work to assess the reliability of the measurement data. Equation (5) was used to ensure the consistency of the measurement data, and Eq. (6) to evaluate the standard error (Seer). The mean, X, number of samples, n, and standard deviation of the measured values were taken from the presented sample set. The experiment was repeated three times for each sample to obtain high precision in the mean RSE value. Table 5 displays the consistency evaluation findings for each measurement, with the maximum RSE range value of 0.62%.

$$RSE\ (\%) = \frac{S_{eer}}{X} \times 100 \tag{5}$$

$$S_{eer} = \frac{\sigma}{\sqrt{n}} \tag{6}$$

Table 5. RSE (%) of the experimental parameters

Compressor Speed (rpm)	Relative Standard Error (%)		
	q_L	W_{in}	COP
2520	0.42796	0.44216	0.36134
2760	0.38019	0.62106	0.44558
3000	0.41592	0.58600	0.41306

3. RESULTS AND DISCUSSION

3.1 Evaluation of Hybrid Nanolubricant Stability

Evaluation of zeta potential shows good stability. These results, compared to previous studies, are shown in Figure 4. According to Ghadimi, et al. [25], the good stability category is 30 - 60 mV, and > 60 mV is excellent. In previous studies, TiO_2-SiO_2/Bio-Glycol showed a zeta potential value of -53.46 mV. The zeta potential value was categorized as good stability because the negative value indicated that the repulsive force was more dominant than the attractive force.

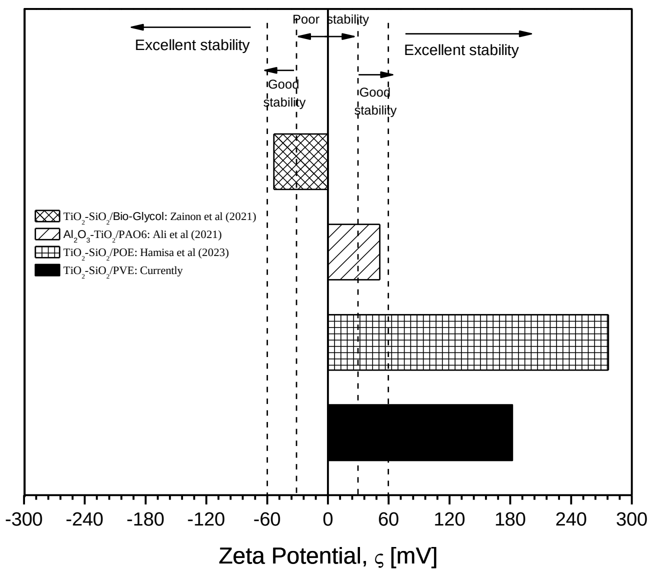


Figure 4. Zeta potential evaluation of hybrid nanolubricant

Meanwhile, Al_2O_3–TiO_2/PAO6 showed a zeta potential value of 51.3 mV; a positive zeta potential value indicated that the attractive force was more dominant than the repulsive force and was categorized as good stability. The absolute value >60 mv (positive and negative) showed that the hybrid nanolubricant was stable because the attractive or repulsive force prevented aggregation or clumping. Furthermore, TiO_2-SiO_2/POE with a volume concentration of 0.1% showed the highest results, 276.8 mV higher than the current study. However, the critical point is that the current study has met the excellent zeta criteria (182.24 mV) recommended by previous researchers [30]. This outcome shows that hybrid nanolubricant has a stable tendency and low coagulation potential [11].

3.2 RAC Performance with PVE/R32

Evaluation of PVE paired with R32 through COP value and power consumption is shown in Figure 5. Where the refrigerant charge of 360 is investigated at a compressor speed between 2520 to 3000 rpm. The results show that COP decreases and power consumption increases with increasing speed. This trend is because the compressor speed affects the mass flow rate. When the compressor speed is increased, the mass flow rate will increase significantly. At the same time, the refrigerant effect decreases drastically, and the compressor work increases to the highest value. Finally, the COP decreases to the lowest level compared to the value resulting from low compressor speed.

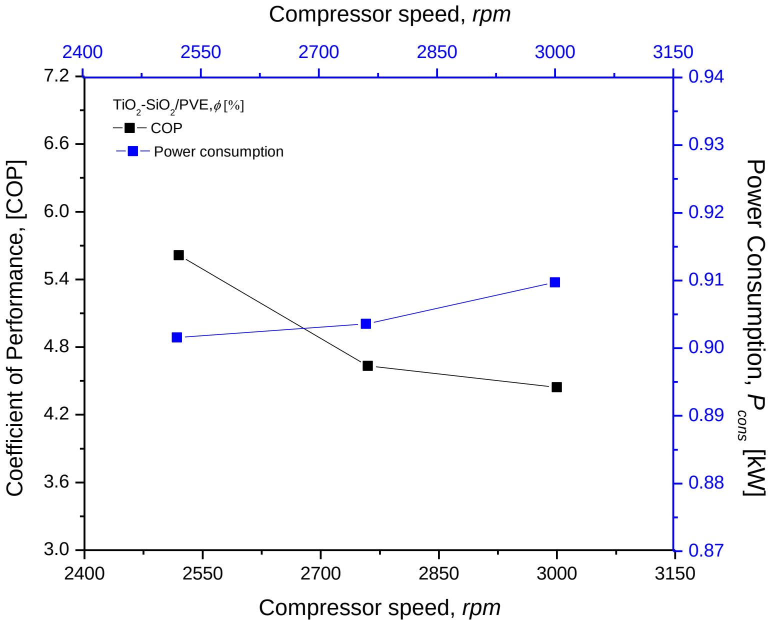


Figure 5. Evaluation of COP dan Power consumption with the different compressor speed

Figure 6 illustrates the *p-h* diagram for a 2520 to 3000 rpm compressor speed. The presentation of the VCR cycle is an ideal refrigeration cycle for a refrigerant charge of 360 g, and each line plot is based on the actual experimental results. These conditions show significant differences in h_1, h_2, and h_6 values. Where the compressor speed affects the discharge pressure, and the p-h plot shows the same tendency. Furthermore, when the suction pressure does not meet the criteria, the discharge pressure will decrease, eventually affecting the refrigerant effect [31]. This situation is likely caused by unbalanced thermal fluctuations that cause a mismatch in system capacity in the compression cycle. The refrigerant suspended in the compressor affects the compression cycle, resulting in slow heat generation in this process. These conditions cause the compressor to work harder, increasing temperature and discharge pressure.

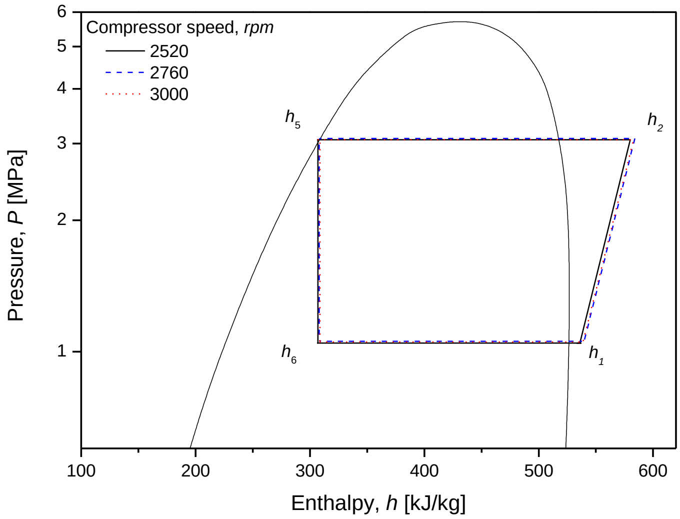
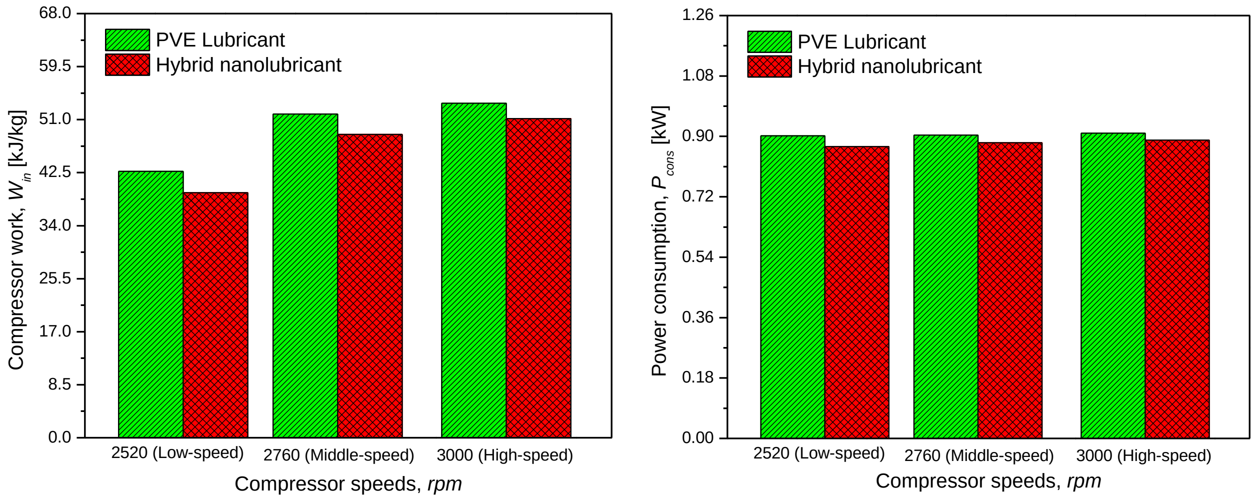


Figure 6. Diagram *p-h* for R32 refrigerant at the different compressor speed

3.3 RAC Performance with Hybrid Nanolubricants

An illustration of compressor work at different compressor speeds is shown in Figure 7 (a). PVE lubricant samples are compared with TiO_2-SiO_2/PVE hybrid nanolubricant, showing an increasing trend. The trend is that compressor work increases with increasing compressor speed. This behaviour is because speed affects the mass flow rate and then impacts the refrigeration effect. Hybrid nanolubricant has a positive impact by reducing compressor work by 8.05, 6.30, and 4.53% at compressor speeds of 2520, 2760, and 3000 rpm, respectively. At low speeds, the percentage of compressor work reduction is higher. This trend is because the swept volume decreases with the frequency given to the compressor. As the compressor speed decreases, the refrigeration effect increases. However, this condition causes a low mass flow rate and a reduced cooling capacity [32] .

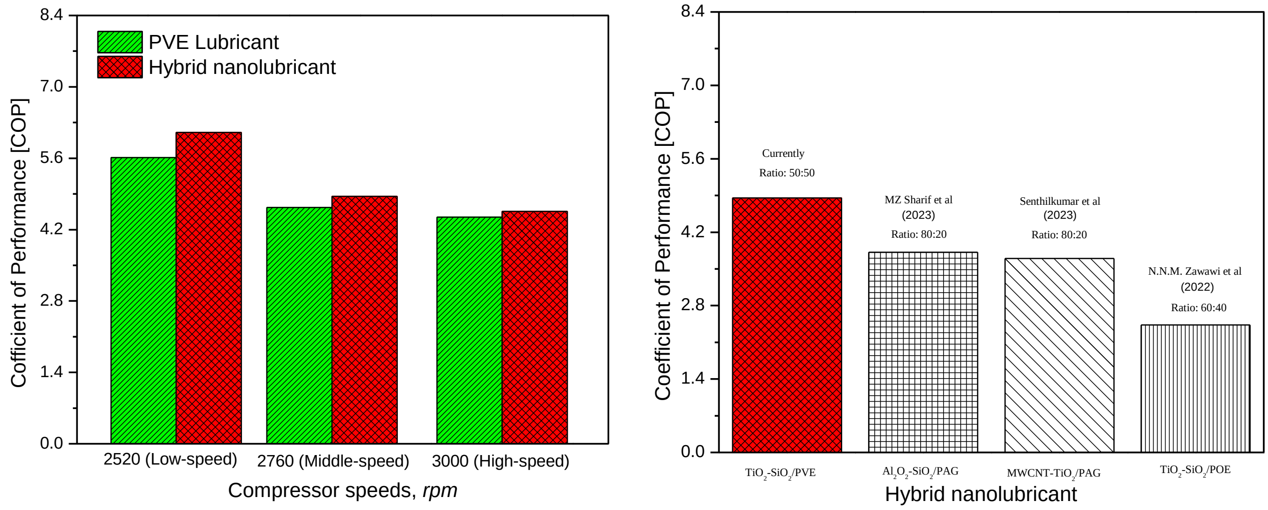
Hybrid nanolubricant has a positive impact in reducing compressor work, whereas nanoparticles as additives have a role in increasing thermal conductivity. When thermal conductivity increases, compressor work decreases. This variation is due to the lubrication system being conditioned with reduced friction and effective heat transfer. At the same time, power consumption will decrease along with the decrease in compressor work. Figure 7(b) shows that power consumption decreases by 3.56% for a compressor speed of 2520 rpm, and for speeds of 2760 and 3000 rpm, power consumption decreases by 2.51 and 2.30%, respectively. These results indicate that compressor speed affects compressor performance, where decreasing compressor work increases energy efficiency. This condition is because when the compressor speed is increased or decreased, it will affect the mass flow rate and the compressor input power [33].



(a) (b)

Figure 7. Evaluation of compressor work and power consumption: (a) Compressor work and (b) Power consumption

TiO_2-SiO_2/PVE hybrid nanolubricant shows better COP than the PVE lubricant shown in Figure 8 (a). At a compressor speed of 2520 rpm, the COP increased by 8.04% and increased by 4.51 and 2.46% for compressor speeds of 2760 and 3000 rpm, respectively. This result indicates that the hybrid nanolubricant can improve the performance of the RAC system. The nature of the nanoparticle additive dispersed into the PVE lubricant can affect the thermal conductivity properties, thereby increasing the compressor work at maximum conditions. In addition, in the case of differences in compressor speeds, there is a significant difference, which is due to the compressor speed linearly affecting the compressor work. High or low speed will affect the compressor's volumetric pressure, affecting the mass flow rate and refrigeration effect [34]. When the refrigeration effect increases, the COP increases as a result.



(a) (b)

Figure 8. Evaluation and comparative COP of hybrid nanolubricant: (a) Experimental COP and (b) Comparison to literature

Figure 8 (b) presents a comparison of the current experimental COP performance with the data from previous studies in the literature. Hybrid nanolubricants have a similar trend. The COP increases compared to the pure lubricant. This outcome confirms that the TiO_2-SiO_2/PVE hybrid nanolubricant has the same trend as the previous studies. The current study has a COP value of 4.852 and an increase of 2.46% at a maximum compressor speed of 3000 rpm. Furthermore, for Al_2O_3–SiO_2/DEC PAG with a binary ratio of 80:20, MWCNT-TiO_2/MO with a binary ratio of 80:20, and TiO_2-SiO_2/POE with a binary ratio of 60:40, the COPs were 3.82, 3.7, and 2.43, respectively [35-37]. These results indicate that the hybrid nanolubricant has satisfactory results in the refrigeration system. Although the working principle of the refrigeration system is similar, different factors of nanoparticle type, base lubricant, concentration volume, and binary ratio result in better COP values. Finally, the hybrid nanolubricant works efficiently in the compressor because its good thermal conductivity makes it optimal for reducing friction, energy loss, and increasing COP [38].

4. CONCLUSIONS

TiO_2 and SiO_2 were dispersed into PVE lubricant using a two-step method, and observations were made on the volume concentration of 0.008% and different compressor speeds. The stability of the hybrid nanolubricant showed satisfactory results, as indicated by the increase in zeta potential value. Hybrid nanolubricant with a binary ratio of 50:50 showed better results than PVE lubricants. The experiment showed these results, where the compressor work decreased by 8.05, 6.30, and 4.53% at compressor speeds of 2520, 2760, and 3000 rpm, respectively. The compressor speed affects the refrigeration cycle, where the compressor work decreases at low speeds. At the same time, power consumption decreases, and COP increases. As a result of this cycle, the power consumption decreased by 3.56, 2.51, and 2.30%, and then the COP increased by 8.04, 4.51, and 2.46% at compressor speeds of 2520, 2760, and 3000 rpm, respectively. Interestingly, the increase in COP using hybrid nanolubricant has been confirmed compared to previous studies. This outcome shows that the use of hybrid nanolubricant shows positive results in improving the refrigeration cycle. It is concluded that TiO_2-SiO_2/PVE hybrid nanolubricant with a binary ratio of 50:50 has provided benefits in improving the performance of the RAC system.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest

AUTHORS CONTRIBUTION

S. Safril (Investigation; Formal analysis; Visualisation; Writing – original draft)

W.H. Azmi (Methodology; Validation; Data curation; Supervision)
Mustakim (Writing – review & editing; Resources)

AVAILABILITY OF DATA AND MATERIALS

The corresponding author makes the study findings and supporting data available upon reasonable request

ETHICS STATEMENT

Not applicable.

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