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RESEARCH PAPER

A Comparative Study on the Cooling Performance of a Split Air Conditioning System Using Nano-Lubricant and Hybrid Nano-Lubricant

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ABSTRACT

The paper provides experimental studies on the possibility of improving the cooling efficiency of a split air conditioning system through the application of advanced lubrication technology. The efficiency of the system is compared to the situation when using three types of lubricants: conventional Pure oil, a mono-particle nano-lubricant (Al_2O_3), and a hybrid nano-lubricant (Al_2O_3- SiO_2). This experiment employed concentricity 0.025 percent of (Al_2O_3) nano and (Al_2O_3- SiO_2). hybrid nanofluid, which has been incorporated into the air conditioning compressor oil. The cooling capacity, compressor work, and the coefficient of performance (COP) were considered as key performance indicators that were tested under controlled experimental conditions. The findings indicate that the concentration of nanoparticles in the lubricant improves the thermo-physical characteristics and heat transfer of refrigeration cycle. Although both the nano-lubricants performed better than the conventional oil, the hybrid nano-lubricant demonstrated the most evidence of improvement reporting a significant rise in the COP as well as a significant decrease in the consumption of energy. The results indicate that hybrid nano-lubricants can be used to a considerable degree to enhance the energy efficiency of vapor compression refrigeration-based systems.

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INTRODUCTION

In many industrial processes, including electricity generation, refrigeration, chemical processing, and automobile cooling, heat exchangers are essential. Their effectiveness is mostly determined by the working fluid's convective heat transfer properties and thermal conductivity. The overall rate of heat transmission is limited by the comparatively poor thermal conductivities of conventional fluids like water, ethylene glycol, or mineral oils. A possible way to enhance heat transfer efficiency in thermal systems is through nanofluids, which are designed colloidal suspensions of nanoparticles within traditional base fluids [1].

Air conditioning has become an indispensable factor in modern constructions and it applies the thermodynamic principles to regulate the indoor temperatures. It extracts the heat indoors and expels it to outside by use of such aspects as evaporators, condensers, compressors, and expansion apparatus. This refrigerant flows through these components and transitions

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through different phases to take in and give out heat effectively. Nano-lubricants have just been introduced in order to improve the performance of air conditioners. Nanoparticles when added to conventional lubricants enhance thermal conductivity and lower friction among parts. The research indicates such nanoparticles increase heat transfer, reduce compressor workloads and energy savings. This technology enhances productivity and improves the lifespan of the machine due to the minimization of the mechanical wear. Nanofluids that blend nanoparticles in base oils are better in thermal properties compared to conventional lubricants. They are useful in sustaining good cooling and ensure that energy consumption remains constant at the various temperatures. Future developments in the air conditioning industry will be based on sustainability by incorporating efficiency of refrigerants and hybrid nano-lubricants. Such innovations are likely to give way to more environmental friendly HVAC systems that can go hand in hand with energy conservation in the world [2-5]. In air conditioning systems, lubrication is necessary, and it decreases friction between moving parts and eliminates wear of such elements as compressors and fans. Maintaining the right lubrication provides efficient operation, enhanced heat transfer, and increased energy efficiency making the cooling process more efficient. The selection of the appropriate lubricant influences the reliability and efficiency of the system. Good lubricants should be highly chemically stable, have a large viscosity range, low pour points and refrigerant-compatible. Ineffective lubricants enhance friction and wear, increase consumption of energy and reduce equipment life. Older polyol ester (POE) oils might not be as thermally conductive and offering enough wear protection as newer product lines such as nano-lubricants. Nano-lubricants would be further refined with the addition of nanoparticles to enhance heat transfer and decrease the viscosity but stay stable in lubrication. This increases the efficiency of compressor work and enhances cooling. Enhanced lubrication is not only ideal in promoting mechanical reliability, but also in the environmental objectives. Nano-lubricants also use fewer quantities thereby reducing wastes and energy use, the carbon footprint is reduced. They are in line with the market need of more environmentally friendly HVAC. Relevant lubrication also enhances the energy efficiency standards by increasing the Coefficient of Performance (COP). The right choice of lubricants can guarantee success in the long run of air conditioning and smarter consumption of energy which is useful to the performance as well as the environment [6-9].

Nano-lubricants form a new generation of lubricating agents, which are designed by solubilizing nanoparticles in an existing lubricating agent medium. These small particles and their sizes (1 to 100 nanometers) are used to enhance the natural characteristics of the base lubricant, resulting in an increase in thermal conductivity, a drop in the forces of friction, and reduction in wear on mechanical parts. The main aim of this integration of nanoparticles is to attain a stage of lubrication performance that cannot be attained with the traditional lubricants alone. In general, the nano-lubricants have been divided into two major groups: mono-particle and hybrid formulations. The mono-particle nano-lubricants of the former are made with only one type of nanoparticle suspended in a base fluid. One of the most spectacular ones is the application of alumina (Al_2O_3) nanoparticles that are popular due to their excellent hardness and thermal resistance. They are especially useful in HVAC systems to reduce friction and increase the heat transfer. On the other hand, hybrid nano-lubricants are prepared through the use of a mixture of different types of nanoparticles in the same lubricant. This method will take advantage of the unique nature of each type of nanoparticle and create a synergist effect, leading to greater overall performance. One of the mostly mentioned examples is a formula that incorporates both alumina (Al_2O_3) and silica (SiO_2) nanoparticles. These hybrid structures have exhibited better lubricity and heat dissipation properties and also have a low viscosity profile.

The effectiveness of a nano-lubricant will depend on a number of important variables, such as the type of nanoparticles employed, the level of this concentration in the mixture, and the properties of the base fluid. Nanoparticles can also be accurately modulated as concentration of particles to accommodate a given application. It has been shown that concentrations of up to about 0.5 percent are often capable of producing significant improvements in performance without influencing the intrinsic properties of the fluid in a negative way. In HVAC systems, these advanced lubricants go beyond the energy savings role.

As mentioned above, they help enhance better thermal control by high heat transfer and increase the service life of equipment by reducing wear and tear of the component. This trend in the area of nano-lubrication is an indicator of the bright future of the technological progress not only in the HVAC technology but also in the area of other branches of engineering since the high-quality lubrication is a fundamental element of creating more resilient, efficient, and sustainable systems [10-11].

The introduction of nano-lubricants into heating, ventilation and air conditioning (HVAC) systems possesses numerous benefits that contribute greatly in improving the performance of the operations in terms of energy savings. The main advantage is that they have high thermal conductivity and hence better heat exchange is promoted in the system. The enhancement of thermal level results in increased strength of heating and cooling processes, hence lowering the total energy consumption.One more important application of nano-lubricants is the reduction of friction between the moving parts of the system, in the compressor, in particular. By reducing this friction, they aid in reduction of wear and tear consequently extending the working life of these critical components. Compared to traditional lubricants that may lose their efficacy when subjected to high temperatures or mechanical force, nano-lubricants do not change their viscosity over time making this another great benefit of the use of these wonderful lubricants. The synergistic benefits of reduced friction and enhanced heat transfer enhance the coefficient of performance (COP) of the HVAC system and enables it to operate to the desired temperature with reduced amount of energy expenditure compared to what would otherwise be utilized with conventional lubricants. This can be translated to significant decreases in the operational costs of the system over the course of the system life.

In addition to these functional advantages, there is also the environmental advantage associated with the use of nano-lubricants. Their great efficiency is also a plausible factor as less of lubricant is necessary to keep them running efficiently hence leading to a reduction of wastes. Moreover, several nano-lubricant recipes are designed to be less toxic and more environmental friendly than their traditional counterparts, which is in line with the modern day sustainability goals. To conclude, nano-lubricants that are used in the HVAC systems are effective in overcoming the numerous constraints of traditional lubrication techniques. This change contributes to the creation of more efficient and environmentally responsible cooling technology that is in a better position to support the new demands of high performance and environmental responsibility [12-18].

MATERIALS AND METHODS

The experiment was performed using a set of two environmentally controlled chambers, as shown in Fig. 1, which is made of two chambers similar in terms of technical design and size. These rooms were made of metal sandwich panels with foam insulation applied on all the surfaces except the south facing wall. This particular wall was made out of 2 mm thick sheet of aluminum. Each chamber had a door on the north side with 4mm glass installed on it. The outer length, width, and height of both chambers were 2 meters, 2 meters and 2.8 meters respectively. Ordinarily, every room had a 2 ton split air conditioning unit. Each unit was fitted with a separate electrical arbitration panel under control of an organizer to control the compressors separately. Both systems had two high-pressure and two low-pressure monitors attached to the arbitration panels. In order to obtain data, each chamber has its own control panel that is connected to an array of six thermocouples that are strategically located in different locations inside the interior space. Moreover, those chambers are equipped with measurement tools to test the voltage and voltage difference to provide a comparative analysis of the amount of power consumed by each system. The first chamber air conditioning unit was used as the control. This system worked using its usual, untouched pressure oil which is known as pure oil. The cooling device in the second chamber, on the contrary, was adjusted to have two compressors with an isolation valve before them. A nano-oil lubricant was loaded to the first compressor and hybrid nano-oil was used in the second compressor. The high pressure inside the systems is operational and depends on the temperature at which the condensation takes place inside the heat exchanger which is usually 12-15 degrees C higher than the ambient external temperature. Two main processes affect the low-pressure parameter: firstly, the type of refrigerant gas (e.g., Freon) that is used in a refrigerator, since each gas has its own unique chemical characteristics, and, secondly, is the evaporation temperature of a refrigerant used in the evaporator at an application. To monitor these pressures, high and low-pressure gauges were affixed to the evaporator outlet in both chambers. Additionally, another set of high and low-pressure gauges was installed at the compressor exit for each unit. The electrical infrastructure for the testing facility is managed by a central power supply board. This board houses main switches, provides control over the operation of the compressors, includes switches for activating and deactivating the cooling units, and is equipped with an alert socket.

Calculation of physical properties of pure oil, nano-oils, and hybrid oils [19-24]

Density

Pure oil density. The pure oil density used in the device of system (1) has been computed by using Eq. 1 where: $\boldsymbol{\rho_f}$ is the density of pure oil, $\mathbf{m_f}$ is the mass of pure oil, and $\mathbf{v_f}$ is the volume of pure oil as shown in Fig. 2

$$\rho_f = \frac{m_f}{v_f} \tag{1}$$

Nano oil, which is a solid nanoparticle of (Al_2O_3) and (Al_2O_3-SiO_2) is made suspended in type 4GS and technical specifications. At the beginning, the amount of oil used in the device was calculated, and the amount of solid nanoparticles was calculated too by using Eqs. 2, 3 and 4 respectively.

$$m_p = \frac{\emptyset \times \rho_p \times (\frac{m_f}{\rho_f})}{1 - \emptyset} \tag{2}$$

$$\rho_p = (1 - \emptyset)\rho_f + \emptyset\rho_n \tag{3}$$

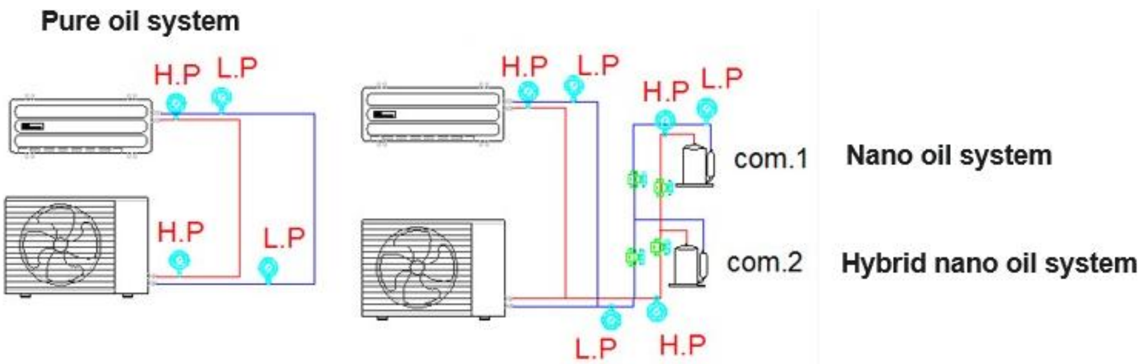

Fig. 1. Test rig.

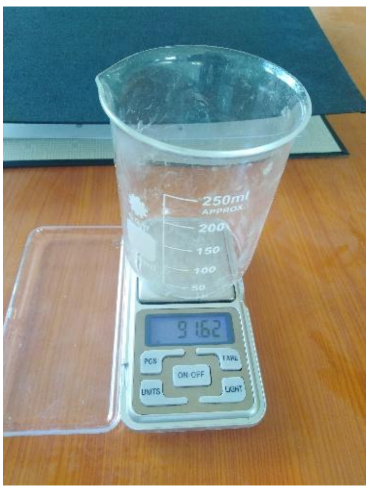
Fig. 2. Density measurement.

$$\rho_{HNF} = \O_{np1} + \O_{np2} \times \rho_{np2} + (1 - \O_{np1} - \O_{np2})\rho_{bf} \quad (4)$$

Viscosity

The viscosity of oil mixed with nanoparticles has been calculated by Eqs. 5 and 6

where: μ_{nf} is nanofluid viscosity, μ_{pf} is pure oil viscosity. Also, Digital Rotational Viscosity Meter device has been used to measure oil viscosity. The viscosity of pure and mixed oil is shown in Fig. 3.

$$\mu_{nf} = \mu_{pf}(1 + 2.5\O) \quad (5)$$

$$\mu_{HNF} = \frac{\mu_{bf}}{(1 - \O_{np1} - \O_{np2})^{2.5}} \quad (6)$$

Nanomaterials preparation method [25-28]

Mechanical Agitation Technique

A high-shear electric mixer, as illustrated in Fig. 4a, was employed for the initial blending process. The base oil was combined with solid nanoparticle quantities, which were precisely determined according to Eq. 2. This mixture was subjected to continuous agitation for a duration of 20 to 45 minutes, or until a visually uniform and completely homogeneous suspension was achieved.

Ultrasonic Homogenization

Following the mechanical mixing stage, the prepared nano-fluid was decanted into three separate flasks (depicted in Fig. 4). These samples were then processed using an ultrasonic device. The ultrasonic treatment was applied for a period ranging from 30 to 50 minutes to ensure optimal dispersion and stability of the nanoparticles within the oil.

Coefficient of performance (COP)

The efficiency of cooling systems and compressors is known as the coefficient of performance, which can be determined by the

Fig. 3. Viscometer device.

Fig. 4. Mechanical and Ultrasonic equipment.

ratio between the power used in the compressor and the amount of useful cooling in the evaporator or the useful heat from the condenser (thermal pump). Eq. 7 has been used to determine the

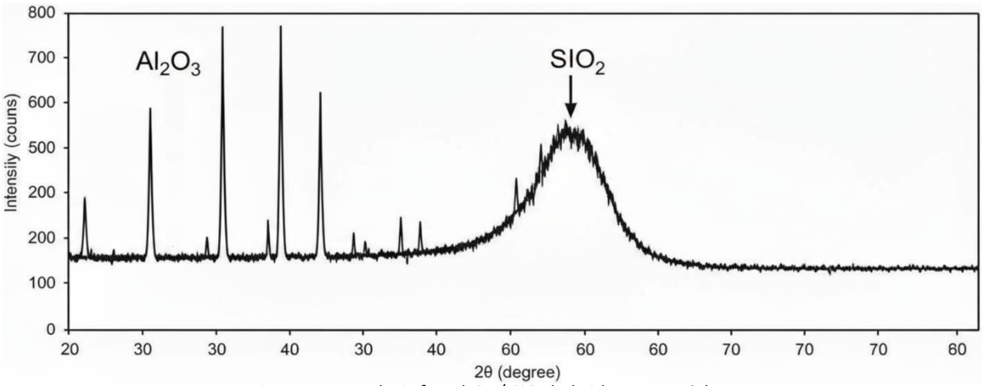

Fig. 5. XRD analysis for Al_2O_3 / SiO_2 hybrid nanoparticles.

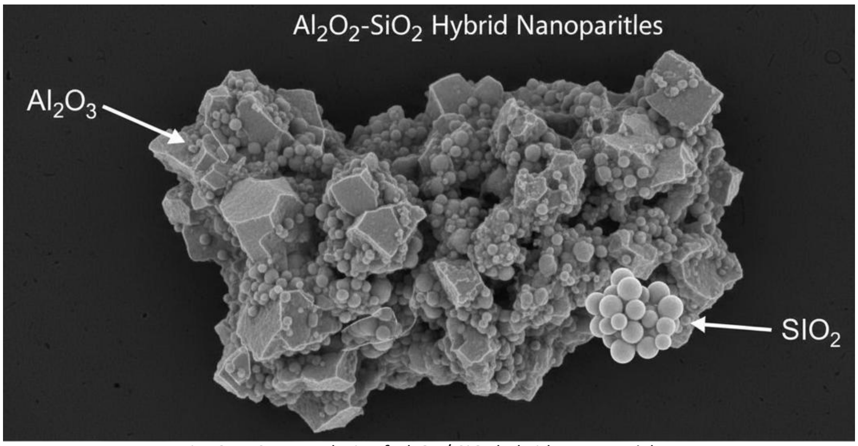

Fig. 6. FESEM analysis of Al_2O_3 / SiO_2 hybrid nanoparticles.

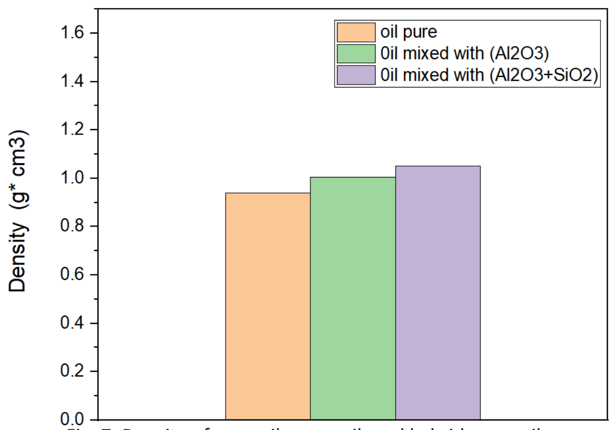

Fig. 7. Density of pure oil, nano-oil, and hybrid nano-oil.

amount of COP for the device using mixed oil and nanoparticles. where Q is the heat supplied to or removed from the reservoir. W is the work done by the compressor.

$$COP = \frac{Q}{W} \quad (7)$$

RESULTS AND DISCUSSION

Fig. 7 shows the density of oil, nano-oil, and hybrid nano-oil. It is clear that the density increases when the nanoparticles are mixed with the oil. This increase reached 2.5% when mixed with nanomaterials, and 4% when mixed with hybrid nano-oil. This indicates that the use of hybrid nanomaterials increases the density of the oil.

Fig. 8 shows the viscosity of oil, nano-oil, and hybrid nano-oil. It is clear that the viscosity

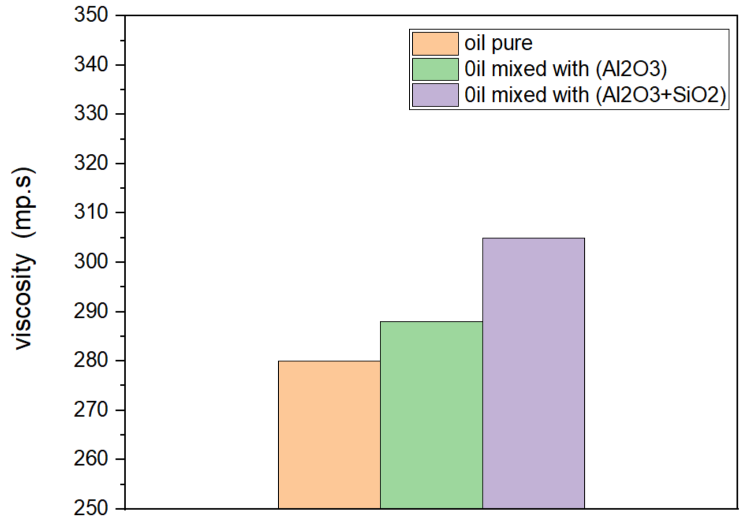

Fig. 8. Viscosity of pure oil, nano-oil, and hybrid nano-oil.

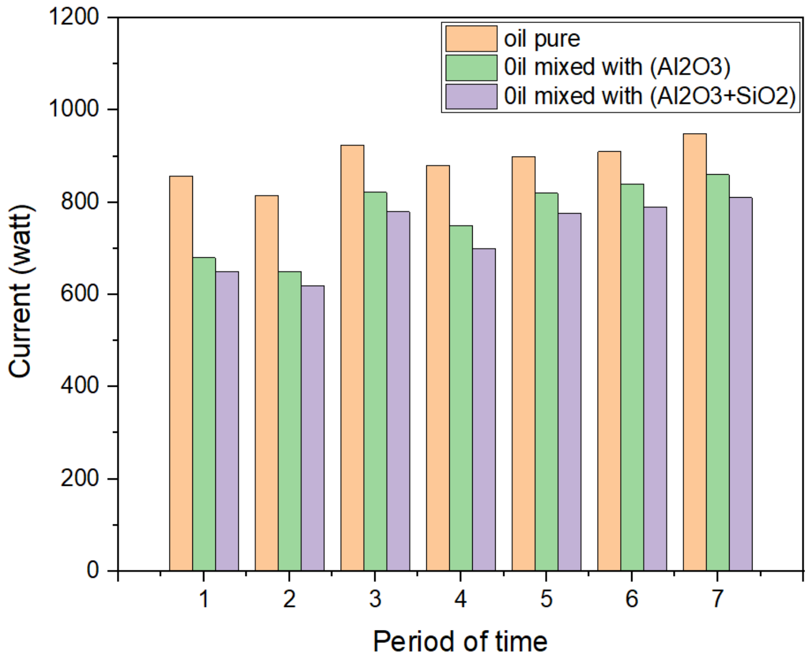

Fig. 9. Current against time period in pure oil, nano-oil, and hybrid nano-oil.

increases when the nanoparticles are mixed with the oil. This increase was (1.8%) when mixed with nanomaterials, and (2.3%) when mixed with hybrid nano-oil. This indicates that the use of hybrid nanomaterials increases the viscosity of the oil.

Fig. 9 shows the electrical current consumption. It is noted that the system operating on pure oil has the highest electrical consumption, while the system operating on nano-oil has reduced electrical current consumption by (20%). The system operating on hybrid nano-oil has reduced electrical current consumption (25%). It has been noted that the best amount of current saved in the system is when using hybrid nano-oil.

Fig. 10 shows a general downward trend for all three lubricants, indicating that they are all cooling down over the measured time period.

The "Oil mixed with (Al_2O_3+SiO_2)" starts at the highest temperature (40°C), followed by the "Oil mixed with (Al_2O_3)" at approximately 37°C, and the "oil pure" at the lowest initial temperature of about 34°C.

Cooling Performance: The "Oil mixed with (Al_2O_3+SiO_2)" (blue line) exhibits the steepest and most consistent decline in temperature. This indicates it has the most effective cooling performance, dissipating heat more rapidly than the other two oils. The data presented in this figure

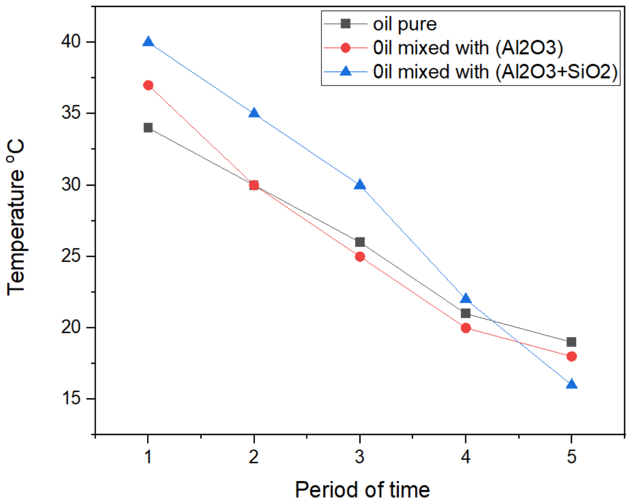

Fig. 10. Temperature against time period in pure oil, nano-oil, and hybrid nano-oil.

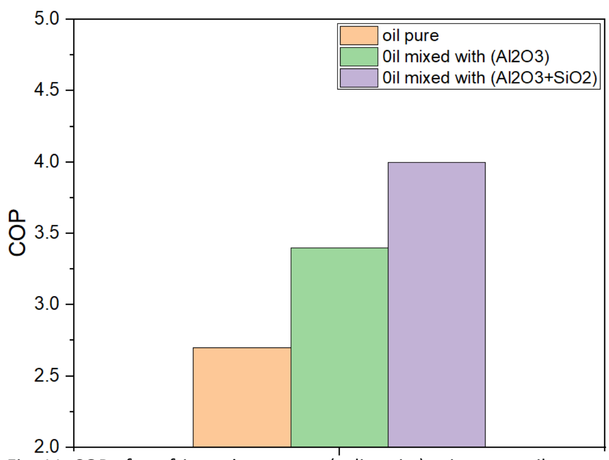

Fig. 11. COP of a refrigeration system (split units) using pure oil, nano-oil, and hybrid nano-oil.

demonstrates that the addition of nanoparticles to the pure oil enhances its cooling properties. The hybrid nano-lubricant ("Oil mixed with Al_2O_3+SiO_2") shows a markedly superior ability to reduce temperature compared to both the pure oil and the oil with a single type of nanoparticle.

Fig. 11 shows that the coefficient of performance (COP) of a refrigeration system (split units) using pure oil, nano-oil, and hybrid nano-oil is 2.7, 3.4, and 4, respectively. The actual COP of the system is evaluated at steady state when the lowest indoor temperature is reached and is calculated from the ratio of the evaporator air conditioning capacity to the total energy consumption. The best COP was observed when using hybrid nano-oil.

Future Technologies of Air conditioning [29-33]

1- is the production of nano-fluids that are more specialized to enhance refrigerant behavior and lessen oil-fouling, which is a recurrent issue that reduces the efficiency of the system. Such high-tech lubricants also not only save energy but also prolong the life of HVAC components by reducing the wear of moving components. Blends of diverse nanoparticles known as hybrid nano-lubricants have also shown fair success in augmenting the coefficient of performance (COP) of the system.

2-These innovations are driven by the quest to achieve sustainability. One of the areas of study is optimization of nanoparticle blends to achieve less energy consumption of compressors without the need to compromise performance in support of the growing need of HVAC technologies that are environmentally friendly.

3- it is vital to review possible health and ecological effects of these materials in their lifecycle. Continued studies are on the importance of exploring the toxicity of nanoparticles in order to determine their safety to the human and the environment.

4- It is possible that in the future, the HVAC technology will focus on using biodegradable base fluids plus nanoparticles to improve its lubrication and stability without posing a new threat to the environment. Research and industry should collaborate to address the issues concerning the stability of nanoparticles as well as to develop definite safety rules. The incorporation of nano-lubricants is one of the major steps that the HVAC sector makes its ecological goals by enhancing energy conservation, reduction of waste, and decreasing its total environmental footprint.

CONCLUSION

Nanoparticles were used in refrigeration compressor lubrication to improve the performance of a split-unit air conditioner. In this study, Al_2O_3 and Al_2O_3-SiO_2 nanoparticles at a mass ratio of 0.002 were suspended in the compressor oil. The study concluded the following:

1. The use of nanoparticles in refrigeration oils provides excellent energy savings, with approximately 25% energy savings when using hybrid nucleic oil compared to pure oil.
2. The use of hybrid nanoparticles in the refrigeration unit oil (split units) contributed to an 18% lower temperature.
3. The coefficient of performance increased by 45% when using hybrid nucleic oil and by 25% when using nucleic oil compared to the standard system.
4. The experimental data were validated with previous data and showed good agreement with a deviation not exceeding 5%.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

REFERENCES

1. Ali FA, Alsaffawi AM, Mohammed KH. The Impact of Alumina Nanoparticles Suspended in Ethylene Glycol on the Performance Efficiency of a Double Pipe Heat Exchanger. Frontiers in Heat and Mass Transfer. 2020;15.
2. Abdullah BN, Soheel AH. CFD Analysis of Improving Air Conditioning System Performance By Adding SiO_2 Nanoparticles To The Compressor Oil. CFD Letters. 2024;17(2):136-147.
3. Said Z, Rahman SMA, Sohail MA, Bahman AM, Alim MA, Shaik S, et al. Nano-refrigerants and nano-lubricants in refrigeration: Synthesis, mechanisms, applications, and challenges. Appl Therm Eng. 2023;233:121211.
4. Safardoust-Hojaghan H, Shakouri-Arani M, Salavati-Niasari M. A facile and reliable route to prepare of lead sulfate nanostructures in the presence of a new sulfur source. Journal of Materials Science: Materials in Electronics. 2014;26(3):1518-1524.
5. Mohseni M, Fathollahi AH. Experimental investigation of Fe_3O_4 nano-oil and outdoor temperature effects on a 5-ton R22 vapor compression chiller performance. Sci Rep. 2025;15(1).
6. Raja NN, Khanderao AD. A review on performance of refrigeration system using nano-refrigerant and nano-lubricant. Chemical Thermodynamics and Thermal Analysis. 2025;20:100222.
7. Althalab H, Ali N, Ebrahim SA, Bahman AM. Air conditioning compressor lubricant enhancement using carbon-based nanomaterials for hot climates. Renewable and Sustainable Energy Reviews. 2025;217:115672.

8. Shewale V, Kapse AA, Barahate SD, Jadhav SP, Suryawanshi SJ. An Experimental Study on the Performance Enhancement of a Heat Pump System using Nanofluids. Engineering, Technology and Applied Science Research. 2024;14(1):12518-12523.
9. Nippon Oil, Sanyo create JV to develop home-use systems. Fuel Cells Bulletin. 2008;2008(1):6.
10. Behnia B, Safardoust-Hojaghan H, Amiri O, Salavati-Niasari M, Aali Anvari A. High-performance cement mortars-based composites with colloidal nano-silica: Synthesis, characterization and mechanical properties. Arabian Journal of Chemistry. 2021;14(9):103338.
11. Hamdallah MW, Jumaah OM, Shaalan ZA, Hussein AM. Performance Enhancement of Air Conditioning (Split Unit) Using CuO/Oil Nano-Lubricant. Mater Sci Forum. 2021;1021:97-106.
12. Mohammed KH, Al-Mirani AE, Ali BM, Alomar OR. Impacts of Using AlO Nano Particle to Compressor Oil on Performance of Automobile Air Conditioning System. Frontiers in Heat and Mass Transfer. 2024;22(3):839-854.
13. Hassanpour M, Salavati-Niasari M, Safardoust-Hojaghan H. Sol-gel synthesis and characterization of Co_3O_4/CeO_2 nanocomposites and its application for photocatalytic discoloration of organic dye from aqueous solutions. Environmental Science and Pollution Research. 2020;28(6):7001-7015.
14. Erdi Korkmaz M, Kumar Gupta M. Nano lubricants in machining and tribology applications: A state of the art review on challenges and future trend. J Mol Liq. 2024;407:125261.
15. Abedalh AS, Shaalan ZA, Saleh Yassien HN. Mixed convective of hybrid nanofluids flow in a backward-facing step. Case Studies in Thermal Engineering. 2021;25:100868.
16. Rashki S, Dawi EA, Zilaei MR, Safardoust-Hojaghan H, Ghanbari M, Ryadh A, et al. ZnO/chitosan nanocomposites as a new approach for delivery LL37 and evaluation of the inhibitory effects against biofilm-producing Methicillin-resistant Staphylococcus aureus isolated from clinical samples. Int J Biol Macromol. 2023;253:127583.
17. Redhwan AAM, Azmi WH, Sharif MZ, Hagos FY. Development of nanolubricant automotive air conditioning (AAC) test rig. MATEC Web of Conferences. 2016;90:01050.
18. Hamisa AH, Azmi WH, Zawawi NNM, Sharif MZ, Shaiful AIM. Comparative Study of Single and Composite Nanolubricants in Automotive Air-Conditioning (AAC) System Performance. IOP Conference Series: Materials Science and Engineering. 2019;469:012044.
19. Sharif MZ, Azmi WH, Zawawi NNM, Ghazali MF. Comparative air conditioning performance using SiO_2 and Al_2O_3 nanolubricants operating with Hydrofluoroolefin-1234yf refrigerant. Appl Therm Eng. 2022;205:118053.
20. Azmi WH, Ismail MF, Zawawi NNM, Mamat R, Safril S. Tribological and residential air conditioning performance using SiO_2-TiO_2/PVE nanolubricant. International Journal of Refrigeration. 2024.
21. Zeml TB, Degu AT. Performance Enhancement and Energy Savings in Domestic Refrigeration Systems Using Al_2O_3 / ZrO_2 Nanoparticle with PAG Oil as a Hybrid Nano Lubricant. ThyssenKrupp techforum. 2025;2025(3):1-12.
22. Zawawi NNM, Azmi WH, Ghazali MF, Ali HM. Performance of Air-Conditioning System with Different Nanoparticle Composition Ratio of Hybrid Nanolubricant. Micromachines. 2022;13(11):1871.
23. Ikumapayi OM, Ogedengbe TS, Laseinde OT, Kazeem RA, Afolalu SA, Ogundipe AT, et al. A concise review on the Suitability of Nano-Refrigerants for Residential Refrigeration Systems (RRS). E3S Web of Conferences. 2023;391:01084.
24. Mohammad-Salehi H, Hamadanian M, Safardoust-Hojaghan H. Visible-Light Induced Photodegradation of Methyl Orange via Palladium Nanoparticles Anchored to Chrome and Nitrogen Doped TiO_2 Nanoparticles. Journal of Inorganic and Organometallic Polymers and Materials. 2019;29(5):1457-1465.
25. Shaalan ZA, Hussein AM, Abdullah MZ. Numerical-experimental study to improve photovoltaic panel cooling by using hybrid ZnO/Al_2O_3 nanofluids. Case Studies in Thermal Engineering. 2025;70:106053.
26. Shaalan ZA, Hussein AM, Abdullah MZ, Alsayah AM, Alshukri MJ, Khaled M. Enhanced photovoltaic cooling using ZnO/TiO_2 hybrid nanofluids: numerical and experimental analysis. International Journal of Thermofluids. 2025;27:101222.
27. Shaalan ZA, Hussein AM, Abdullah MZ. Enhancing PVT System Performance with Hybrid Grp/Al_2O_3 Nanoparticles. Journal of Mechanics of Continua and Mathematical Sciences. 2025;20(1).
28. Shaalan ZA, Hussein AM, Abdullah MZ, Noor MM. Evaluation of Stability and Enhancement of Nano Fluid Methods. Journal of Physics: Conference Series. 2024;2688(1):012016.
29. Aljuwayhel NF, Ali N, Bahman AM. Experimental evaluation of split air conditioning performance using nanodiamonds particles in compressor polyester lubricant oil. Appl Therm Eng. 2023;231:120961.
30. Harichandran R, Paulraj P, Maha Pon Raja S, Kalyana Raman J. Effect of h-BN solid nanolubricant on the performance of R134a–polyolester oil-based vapour compression refrigeration system. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2019;41(3).
31. Senthilkumar A. Prediction and performance enhancement of R600a refrigerator adopting machine learning algorithms. Research on Engineering Structures and Materials. 2025.
32. Nugroho A, Mamat R, Xiaoxia J, Bo Z, Jamlos MF, Ghazali MF. Performance enhancement and optimization of residential air conditioning system in response to the novel FAl_2O_3-POE nanolubricant adoption. Heliyon. 2023;9(10):e20333.
33. Senthilkumar A, Abhijith EP, Jawhar CAA, Jamshid. Experimental investigation of Al_2O_3/SiO_2 hybrid nanolubriant in R600a vapour compression refrigeration system. Materials Today: Proceedings. 2021;45:5921-5924.