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Original Article

An Investigation of Nanolubricants R600a-Polyolester Oil-GO and R600a-Polyolester Oil-TiO_2. Thermophysical Properties

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Abstract - *In recent years, nanoparticles have been demonstrated to be one of the most effective means of enhancing the heat transfer and thermophysical properties of conventional coolants and lubricants. Metallic or metal oxide particles, carbon, and its allotropes dispersed in conventional lubricating oils form nanolubricants. A study was conducted using R600a (isobutane) as a working fluid to experiment with different concentrations of GO and TiO_2 nanoparticles dispersed in polyolester oil lubricant. Two samples were prepared, each containing 0.3 g/l of GO and TiO_2 nanolubricant. We investigated nanolubricant concentrations in 30 grams, 40 grams, and 50 grams of R600a refrigerant, respectively. The primary components of the refrigerator were equipped with Type K thermocouples. Additionally, the compressor is fitted with pressure gauges at the inlet and outlet to monitor discharge and suction pressures. In this research, the efficacy of the lubricant was compared with that of the original base lubricant (POE oil). The results indicated that the graphene oxide nanolubricant at 0.3 g/L achieved the optimal Coefficient Of Performance (COP), the lowest temperature in the evaporator, and the minimum power usage compared to the TiO_2 nanolubricant.*

Keywords - *Graphene-oxide, GO composite nanoparticles, Polyolester (POE) oil, Nano lubricants, Natural refrigerant, R600a (isobutane) refrigerant.*

1. Introduction

Energy efficiency is the primary issue with the vapour compression refrigeration system. An enormous amount of electricity is required when it comes to refrigeration and other uses. New technologies like nanolubricants and nano refrigerants will improve the efficient usage and efficiency of energy. The formation of nano refrigerants and nano lubricants is created by combining nanoparticles with regular refrigerants and lubricating oils to generate them. It is important to note that scattering these nanoparticles has many advantages, such as the use of less energy in the compressor, the increase in the coefficient of performance, and the enhancement of heat transfer properties [1]. Refrigeration systems have a big influence on modern living. Apart from offering cozy and hygienic living spaces, it is also considered crucial for withstanding severe weather conditions and food preservation [2]. Today's society depends more than ever on refrigeration systems to keep people comfortable while they work or live. Global warming, a rise in temperatures, and a rise in living standards, especially in developing nations, are the primary causes of these phenomena [3, 4]. Globally, there is an imminent deadline for phasing out and restricting the use of harmful working fluids (refrigerants). As refrigeration systems are ozone-depleting and have high global warming potential, researchers have recently been exploring natural refrigerants (especially hydrocarbon-based types) [5, 6]. The following are just a few of the reasons why hydrocarbon working fluids are becoming more widely adopted: (i) minimal contribution to global warming and no depletion of the ozone layer [7]. (ii) The performance of the system was improved with a smaller mass charge [8]; (iii) the ability to integrate with existing sub-components [9]; and (iv) enhancing the performance of the energy-exergy system [10]. However, a key barrier to their broad acceptance in small- to medium-sized refrigeration applications is that the handling of hydrocarbon-based refrigerants presents several flammability challenges. As a result, the contemporary literature is replete with attempts to address these flammability issues. Concerns of flammability related to hydrocarbon consumption, as stated by Corberán et al. [11], in addition to the lower operating temperatures and pressure conditions of smaller domestic refrigerators (below 150 g), are negligible since they can be placed in any part of the house and operated at any temperature. In Ohunakin et al.

[12], According to the regulations, hydrocarbon-based refrigerants may be used in domestic refrigerators under the following conditions: (a) Seal the hydrocarbon refrigerant system and reduce linkages. (b) Maintaining a minimal hydrocarbon charge, (c) Reducing the concentration of HC below its flammability threshold in the ambient air through the utilization of a ventilation system, and (d) Removing the system's source of ignition.

Recent advancements in nanotechnology may offer an alternate method of enhancing the performance of vapor compression refrigeration systems using fluid additives such as nanoparticles (1–100 nm). Nanoparticles, or metal or metal oxide particles, range in size from 1 to 100 nm and are made feasible by nanotechnology. The term "Nanofluid" was introduced by Dr. Choi at Argonne National Laboratory to describe the colloidal dispersion of nanoparticles with ordinary fluids [13]. There are several heat transfer applications in which nanofluid is in high demand, such as renewable energy systems, air conditioning, refrigeration, cars, electronics cooling, etc., because it has superior thermal conductivity and specific heat properties. [14].

Nanoparticle applications have revolutionized the engineering industry by significantly improving system performance. With a range of innovative solutions available, it is no surprise that nanoparticles are becoming increasingly popular in the field of engineering.

Xuan and Li [15] show that nanoparticles exhibit superior properties and characteristics when compared to ordinary materials due to their unique nanostructural properties. Hu et al. [16] discovered that the compressor's power usage is closely correlated with the lubricating oil's friction coefficient. By lowering the lubricating oil's friction coefficient, the use of nanoparticles lowers compressor energy consumption and raises the refrigerator's coefficient of performance. Subhedar and Raman [17] The addition of nanoparticles was observed to enhance the thermal conductivity of the base fluid. It will be different when using different kinds and volume fractions of nanoparticles to accomplish heat transfer.

In recent decades, several alternative strategies have been suggested to enhance the system's cooling efficiency, including incorporating nanoparticles (1–100 nm) as a possible alternative strategy. Metal nanoparticles, also known as metal oxide nanoparticles, have been shown to improve heat transfer efficiency [18]. Incorporating nanoparticles into refrigeration systems can be accomplished in two ways: one-step and two-step. Creating and distributing nanoparticles within a base fluid is possible using a one-step process. During a two-step procedure, nanoparticles are separately produced and then disseminated to ensure stability. In general, the use of a two-step approach instead of a one-step approach is preferred in most cases [19].

In certain studies, it has been suggested that nanoparticles may be used as additives to lubricating oils. According to the experiment's results, Senthilkumar et al. [20] ANFIS and artificial neural networks were used in this study, neither of which has been effectively implemented before. It was discovered that the cooling effect anticipated by the ANN model increased by 50% when 0.4 g/L of Multi-Walled Carbon Nano Tube (MWCNT) / Titanium dioxide (TiO_2) composite nanofluids were added to the system, from 110 to 210 W. Babarinde et al. [21] Graphene nanolubricants are used in household refrigerators to optimize propane and butane blends.

According to the data, there was a decrease in compressor input for the refrigerator system, ranging from 13.1% to 32.5%, while the refrigeration effect experienced an increase between 3.5% and 17.2%. Saravanan et al. [18] performed experimental studies with a household refrigerator containing Al_2O_3 and TiO_2 nanoparticles at different concentrations within a base lubricant (POE oil) in varying concentrations. This study demonstrates that the best performance with a lubricant made up of nanocomposite materials (50% Al_2O_3/50% TiO_2/POE oil) for R134a (tetrafluoroethane) is achieved by using nanocomposite materials (50% Al_2O_3/50% TiO_2/POE oil). With the lowest irreversibility (36.19 kJ/kg), power consumption (92.2 W), and compressor work (61.24 kJ/kg) of all the systems, this one achieved a second-law efficiency of 40.9%. Babarinde et al. [22] The basic lubricant (mineral oil) was mixed with graphene nanoparticles. When compared with mineral oil, graphene nanolubricants have lower evaporator temperatures, lower refrigeration energy consumption, and higher efficiency.

Adelekan et al. [23] Nanoparticles of Titanium dioxide (TiO_2) were used in an experiment using R600a (isobutane). During the investigation, a number of characteristics were established, such as the discharge temperature and COP ranges, which were 3.23–4.03 and 50–62°C, respectively. Subhedar et al. [24] This experiment looked at the R-134a refrigerant's efficiency in a refrigeration system that was lubricated with mineral oil containing different percentages of Al_2O_3 (0.05%, 0.075%, 0.1%, and 0.2%). Compared to base fluid, the nanolubricant improves COP by 85%. Zhelezny et al. [25,26] Nanoparticles of Al_2O_3 and TiO_2 were used to evaluate isobutane (R600a) at a wide range of temperatures and concentrations.

In a recent study, it was shown that nanoparticles can significantly lower the surface tension and increase the viscosity of refrigerant/oil mixtures. Narayanasarma et al. [27,28] The application of SiO_2 nanoparticle suspensions in POE oil used in refrigerant compressors as nano lubricants was assessed experimentally. Among these aspects were thermal performance, corrosion resistance, rheological stability, oxidative stability, and environmental friendliness.

POE/SiO_2 nanolubricants' thermal conductivity increases as temperature and mass rise.

This study aims to evaluate the efficiency of a refrigeration system by analyzing its performance with R600a as the refrigerant and a nanolubricant that contains GO and TiO_2 as the lubricant.

2. Methodology

2.1. Experimental Test Set-Up

A vapour compression refrigeration test apparatus is depicted in Figure 1. It is made up of an expansion device, a condenser, a compressor, and an evaporator unit with an evaporator coil to cool the water within.

Thermocouples measured condenser inlet and outlet, water tank, and evaporator temperatures. Evaporator and condenser pressures were measured with two pressure gauges. An energy meter was used to calculate the refrigeration system's power usage. Table 1 shows the instrument's uncertainty.

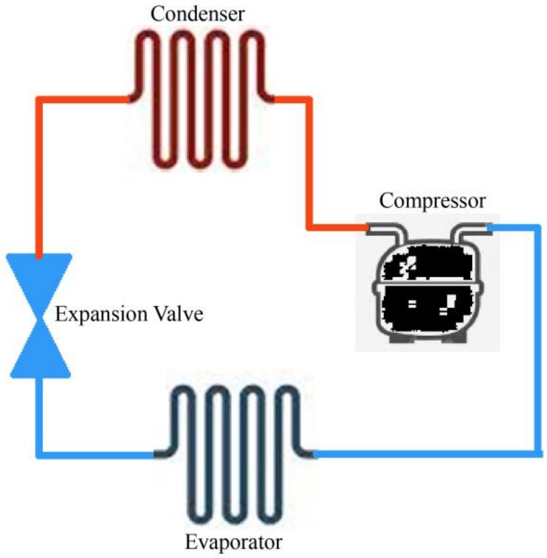

Fig. 1 Diagram of the experimental test rig

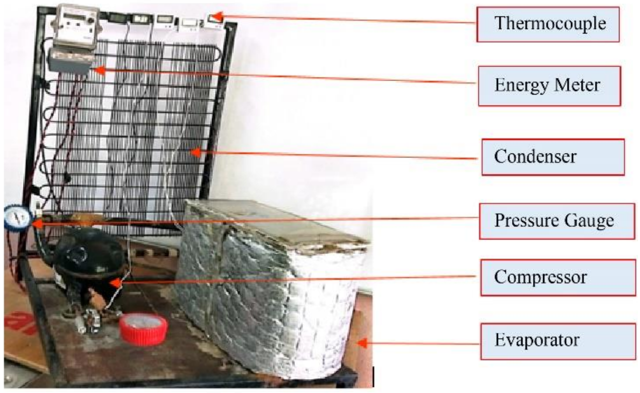

Fig. 2 Test rig setup

Table 1. Measuring instruments have uncertainty

Sr. No.	Measuring Device	Range	Lack of certainty
i	Pressure Gauge	0 – 2500 kPa	±1%
ii	Thermocouple	-400C – 6000C	±3%
iii	Wattmeter	1-2500 W	±1%

100 g of R134a refrigerant is planned to be used in the experimental test setup. The system was fully flushed and cleaned out using a vacuum pump. Because of its very low GWP and zero ODP, R600a refrigerant is taken into consideration in this test configuration. The bulk limit of hydrocarbon refrigerants is 150 g due to flammability. The mass charges for R600a are between 30 and 50 grams since it has a lower density than R134a. Because Polyolester Oil (POE) is compatible with both R600a and the refrigerator components, it was selected as the primary lubricant for this experiment. This test rig is designed to operate with 100 grams of R134a refrigerant. It is an experimental setup.

For this experimental test setup, a pressure of 60 to 70 bars was applied to nitrogen (N_2) gas, and this pressure was maintained for two hours. As a consequence, no system leaks were found. Nitrogen (N_2) gas was extracted from the system to complete its evacuation. Through the connection of a vacuum pump to the compressor's port, the entire system was evacuated to remove any contaminants. Every study was conducted using the same method. During the charging process, the charging line was filled up with R600a refrigerant, which was attached to the compressor. A 10-minute period of time in which the system had to stabilize was allotted to it every time the system had to stabilize. We determined the efficiency of the system using Equations (1), (2), and (3):

$$\text{Refrigeration Effect} = \frac{mC_{pw}(T_i - T_f)}{t} \text{ kW} \quad (1)$$

$$\text{Work Input} = \frac{(E_f - E_i) * 3600}{t} \text{kW} \quad (2)$$

$$\text{COP} = \frac{\text{Refrigeration effect}}{\text{Work Input}} \quad (3)$$

2.2. Nanolubricants Prepared from Graphene Oxide and Titanium Dioxide

A nanolubricants preparation process is the most fundamental step in its study as it affects its properties and stability. Some special methods are required to prepare the nanolubricant so that it will be uniform and stable, as well as have fewer problems with agglomeration and sedimentation. The process of dispersing GO/TiO_2 nanoparticles in base fluids like polyolester oil results in a nanolubricant, which is utilized in the refrigeration system. Preparation of nanolubricants involves two main methods: one-step and two-step. Creating nanoparticles and dispersing them in the liquid happens at the same time in a one-step method. This method is commonly used for the preparation of nanolubricants and can be a more straightforward approach to production. Utilizing the two-step method, the stability of the nanofluid is preserved by initially synthesizing the nanoparticles separately and subsequently dispersing them in the liquid. While the two-step method entails a longer duration than the one-step procedure, it can lead to a more enduring nanofluid stability. A flowchart for producing nanofluids is shown in Figure 3. In general, two-step methods are preferred over single-step methods because they are more efficient [19].

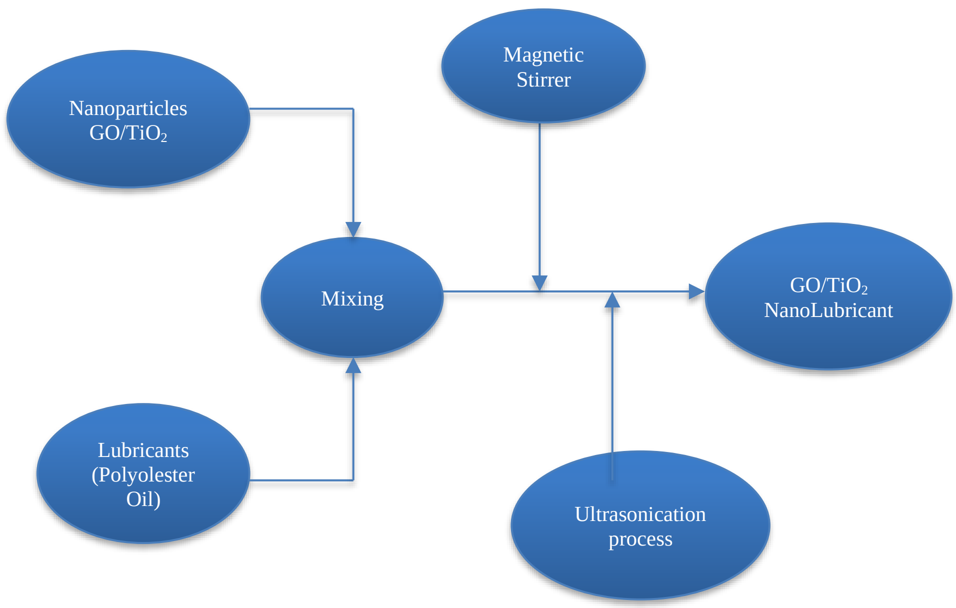

Fig. 3 Flow chart for the preparation of GO/TiO_2 nanolubricants

2.2.1. Titanium Dioxide (TiO_2) Nanolubricant

The most important step in experimental research is the production of nanolubricants. In the present study, titanium dioxide was added to polyolester oil to make nanolubricants. 20–40 nm-sized titanium dioxide nanoparticles are used. Table 2 lists the titanium dioxide nanoparticle's thermo-physical properties.

Table 2. Properties of titanium dioxide used in this study

Properties	Description
Purity	99.9%
Mean Size of Particles	20 nm to 40 nm
Molecular Weight	79.8658 g/mol
Physical State	Powder
Melting Point	1,843 degrees Celsius
Physical Form	Powder
Colour	White

2.2.2. Graphene Oxide (GO) Nanolubricant

In the present study, graphene oxide was added to polyolester oil to make nanolubricants. Ad-Nano Technologies provided 0.8–2 nm-sized graphene oxide nanoparticles. The employed graphene oxide nanoparticle's thermos-physical properties are listed in Table 3. SEM images of graphene oxide nanopowder are shown in Figure 4.

Table 3. Graphene oxide properties

Properties	GO Nano Powder
Purity	99.9%
Thickness	0.8-2 nm
Layers	1 to 3
Amount of Carbon	60 to 80%
Amount of Oxygen	15 to 32%
Odour	Odourless
Colour	Black Powder
Surface Area	110 to 250*m^2/g

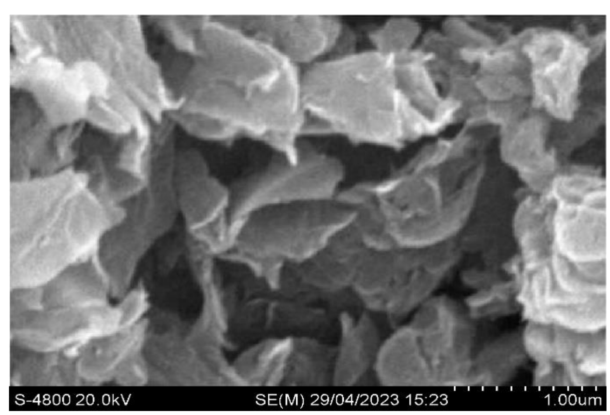

Fig. 4 SEM of graphene oxide

In the present work, one liter of polyolester oil is accustomed to creating two distinct samples with nanolubricant quantities of 0.3 g/L of GO and TiO_2. With a measurement range of 0.001 to 110g, a digital weighing scale was used to weigh each nanoparticle. Titanium dioxide and graphene oxide nanoparticles were combined with polyolester oil at 0.3 g/L of concentration. In order to enhance the even distribution of nanoparticles within the lubricant, the nanolubricants were subsequently subjected to 60 minutes at room temperature while being stirred at 1200 rpm on a magnetic stirrer.

Using a magnetic stirrer as assistance, the nanoparticles are mixed with lubricating oil at varying concentrations. Then, the bound nanoparticles in the lubricant are properly mixed and separated using an ultrasonication process.

The nanolubricant's stability was assessed by conducting a sedimentation test. After continuous observation over five days, no sedimentation occurred, confirming the sustained visual stability of the nanolubricant.

3. Findings and Discussion

The system's performance was assessed using different Polyolester (POE) oil/R600a nanolubricant concentrations and R600a mass charges. Figure 5 depicts the power usage of the compressor at different concentrations of nanolubricant. The power requirements were determined using pure oil, graphene-oxide nanolubricant, and titanium dioxide nanolubricant at 0.3 g/L each. The system consumed the least power when 0.3 g/L graphene oxide nanolubricant was combined with 40 grams of R600a. In contrast, the system used 50 grams of R600a and required 0.155 kW more power.

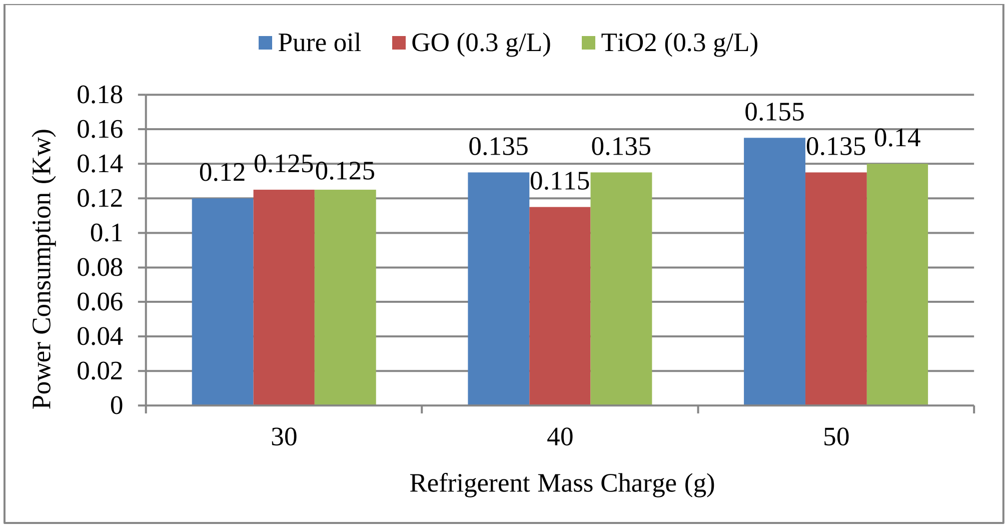

Fig. 5 Power consumption of the system using Go/TiO_2 nanolubricant

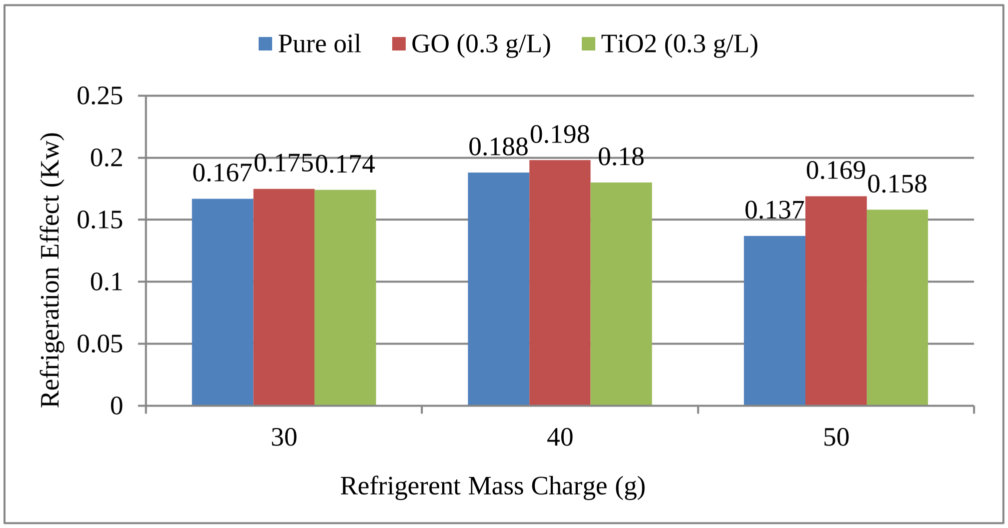

Fig. 6 Refrigeration effect of the system using Go/TiO2 nanolubricant

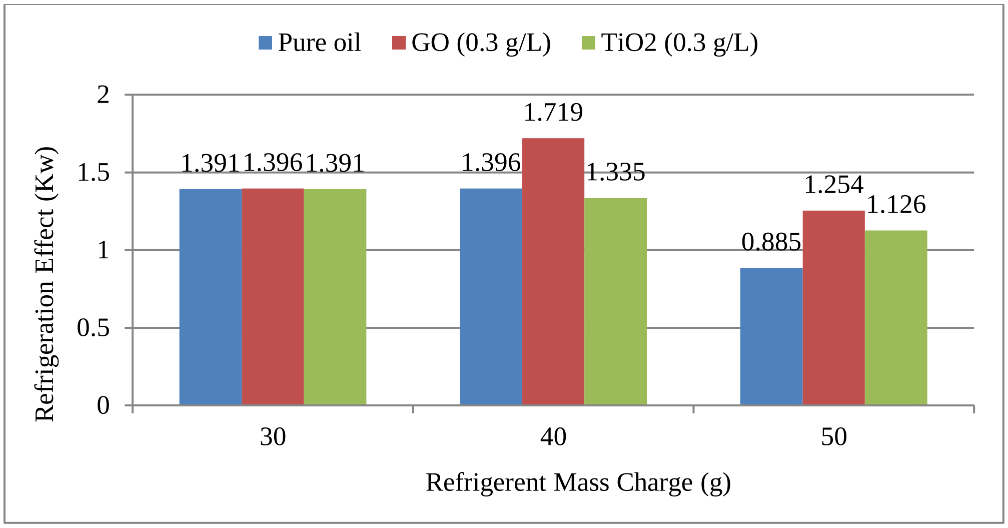

Fig. 7 Coefficient of performance of the system using Go/TiO_2 nanolubricant

Figure 6 shows a graph that illustrates the system's refrigeration effect. With a mass charge of R600a, the nanolubricant GO/TiO_2 exhibits greater cooling characteristics than the base lubricant. The refrigeration effect increases with increasing thermal conductivity of a lubricant containing GO/TiO_2 nanoparticles. Graphene oxide nanolubricant 0.3 g/L achieves a maximum refrigeration effect of 0.198 kW with a 40g mass charge of R600a. Based on the results of this experiment, R600a mass charges of 30, 40, and 50 g result in the lowest refrigeration effects for pure oil (polyolester oil), generating 0.167, 0.18, and 0.137 kW, respectively.

When choosing a substitute refrigerant, one of the most crucial things to take into account is its Coefficient of Performance (COP). In other words, it can be defined as the ratio between the refrigeration effect and the energy usage of the refrigeration system. In Figure 7, the system's COP values are displayed. In graphene-oxide lubricants, R600a has a higher Coefficient of Performance (COP) than TiO_2 and base lubricants. The ranges of COP are 0.88 to 1.25, 1.39 to 1.40, and 1.39 to 1.72, in that order. With 0.3 g/L graphene-oxide nanolubricant, 1.72 COP was achieved. The system's graphene-oxide nanolubricant contributed to the increased COP by consuming less power and having a better cooling effect.

4. Conclusion

In an experimental investigation, the effectiveness of GO/TiO2 nanolubricant and base lubricant was compared and assessed using metrics related to power consumption, cooling effect, and coefficient of performance (COP) in a test configuration. Various combinations of GO/TiO2 nanolubricant at concentrations of 0.1, 0.3, and 0.5 g/L were tested alongside R600a refrigerant masses of 30, 40, and 50 g. Our experimental results have shown that increasing GO/TiO2 nanolubricant concentrations enhanced the refrigeration system's vapour compression performance.

- R600a mass charges and concentrations of GO/TiO2 nanoparticles were safely tested in a vapor compression refrigeration test rig.
- Reduced power consumption and evaporator temperatures were noted when GO/TiO2 nanolubricant was applied at concentrations of 0.1, 0.3, and 0.5 g/L. This suggests that R600a-using refrigeration systems can use GO/TiO2 nanolubricant in place of polyolester oil.
- Due to its efficient performance in terms of power consumption, refrigeration effect, and Coefficient of Performance (COP), graphene-oxide nanolubricant can replace polyolester oil in the vapour compression refrigeration test rig.

References

[1] A. Senthilkumar, A. Anderson, and R. Praveen, “Prospective of Nanolubricants and Nano Refrigerants on Energy Saving in Vapour Compression Refrigeration System – A Review,” *Materials Today: Proceedings*, vol. 33, pp. 886-889, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[2] B.O. Bolaji, and Z. Huan, “Ozone Depletion and Global Warming: Case for the Use of Natural Refrigerant – A Review,” *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 49-54, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[3] Hanlong Wan et al., “A Comprehensive Review of Life Cycle Climate Performance (LCCP) for Air Conditioning Systems,” *International Journal of Refrigeration*, vol. 130, pp. 187-198, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[4] Nawaf F. Aljuwayhel et al., "Experimental Investigation of Thermophysical Properties, Tribological Properties and Dispersion Stability of Nanodiamond-Based Nanolubricant for Air Conditioning Systems," *International Journal of Refrigeration*, vol. 145, pp. 325-337, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] James M. Calm, "The Next Generation of Refrigerants – Historical Review, Considerations, and Outlook," *International Journal of Refrigeration*, vol. 31, no. 7, pp. 1123-1133, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[6] D.S. Adelekan et al., "Experimental Investigation of a Vapour Compression Refrigeration System with 15nm TiO2-R600a Nano-Refrigerant as the Working Fluid," *Procedia Manufacturing*, vol. 35, pp. 1222-1227, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[7] Olayinka S. Ohunakin et al., "Experimental Investigation of TiO2-, SiO2- and Al2O3-Lubricants for a Domestic Refrigerator System Using LPG as Working Fluid," *Applied Thermal Engineering*, vol. 127, pp. 1469-1477, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[8] Mehdi Rasti, SeyedFoad Aghamiri, and Mohammad-Sadegh Hatamipour, "Energy Efficiency Enhancement of a Domestic Refrigerator Using R436A and R600a as Alternative Refrigerants to R134a," *International Journal of Thermal Sciences*, vol. 74, pp. 86-94, 2013, [CrossRef] [Google Scholar] [Publisher Link]

[9] Damola S. Adelekan et al., "Experimental Performance of LPG Refrigerant Charges with Varied Concentration of TiO2 Nano-Lubricants in a Domestic Refrigerator," *Case Studies in Thermal Engineering*, vol. 9, pp. 55-61, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Jatinder Gill, and Jagdev Singh, "Component-Wise Exergy and Energy Analysis of Vapor Compression Refrigeration System Using Mixture of R134a and LPG as Refrigerant," *Heat and Mass* Transfer, vol. 54, no. 5, pp. 1367-1380, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[11] Jose M. Corberán et al., "Review of Standards for the Use of Hydrocarbon Refrigerants in A/C, Heat Pump and Refrigeration Equipmentutilisation Des Frigorigènes," *International Journal of Refrigeration*, vol. 31, no. 4, pp. 748-756, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[12] Olayinka S. Ohunakin et al., "Performance of a Hydrocarbon Driven Domestic Refrigerator Based on Varying Concentration of SiO2 Nano-Lubricant," *International Journal of Refrigeration*, vol. 94, pp. 59-70, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[13] S.U. Choi, and J.A. Eastman, "Enhancing Thermal Conductivity of Fluids with Nanoparticles," *Conference: 1995 International Mechanical Engineering Congress and Exhibition*, San Francisco, CA (United States), 1995. [Google Scholar] [Publisher Link]

[14] Wei Yu, and Huaqing Xie, "A Review on Nanofluids: Preparation, Stability Mechanisms, and Applications," *Journal of Nanomaterials*, vol. 2012, no. 1, pp. 1-17, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[15] Yimin Xuan, and Qiang Li, "Investigation on Convective Heat Transfer and Flow Features of Nanofluids," *Journal of Heat Transfer*, vol. 125, no. 1, pp. 151-155, 2003, [CrossRef] [Google Scholar] [Publisher Link]

[16] Z.S. Hu et al., "Preparation and Tribological Properties of Nanometer Magnesium Borate as Lubricating Oil Additive," *Wear*, vol. 252, no. 5-6, pp. 370-374, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[17] Dattatraya Subhedar, and Bharat Ramani, "Experimental Investigation on Thermal Conductivity and Viscosity oF Al^ sub 2^ O^ sub 3^/Mono Ethylene Glycol and Water Mixture Nanofluids as a Car Radiator Coolant," *Advances and Applications in Fluid Mechanics*, vol. 19, no. 3, pp. 575 - 587, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[18] K. Saravanan, and R. Vijayan, "Performance of Al2O3/TiO2 Nano Composite Particles in Domestic Refrigerator," *Journal of Experimental Nanoscience*, vol. 13, no. 1, pp. 245-257, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[19] Atul Bhattad, Jahar Sarkar, and Pradyumna Ghosh, "Improving the Performance of Refrigeration Systems by Using Nanofluids: A Comprehensive Review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3656-3669, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] A. Senthilkumar et al., "Enhancement of R600a Vapour Compression Refrigeration System with MWCNT/TiO2 Hybrid Nano Lubricants for Net Zero Emissions Building," *Sustainable Energy Technologies and Assessments*, vol. 56, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[21] T.O. Babarinde, D.M. Madyira, and P.M. Mashinini, "Performance Evaluation of Graphene-Enhanced LPG in a Vapour Compression Refrigeration System: An Experimental Approach," *Energy Reports*, vol. 8, pp. 1226-1235, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[22] T.O. Babarinde et al., "Enhancing the Energy Efficiency of Vapour Compression Refrigerator System Using R600a with Graphene Nanolubricant," *Energy Reports*, vol. 6, pp. 1-10, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[23] D.S. Adelekan et al., "Performance of a Domestic Refrigerator Infused with Safe Charge of R600a Refrigerant and Various Concentrations of TiO2 Nanolubricants," *Procedia Manufacturing*, vol. 35, pp. 1158-1164, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Dattatraya G. Subhedar, Jinalkumar Z. Patel, and Bharat M. Ramani, "Experimental Studies on Vapour Compression Refrigeration System Using Al2O3/Mineral Oil Nano-Lubricant," *Australian Journal of Mechanical Engineering*, vol. 20, no. 4, pp. 1136-1141, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[25] V.P. Zhelezny et al., "A Complex Investigation of the Nanofluids R600a-Mineral oil-AL2O3 and R600a-Mineral Oil-TiO2. Thermophysical Properties," *International Journal of Refrigeration*, vol. 74, pp. 488-504, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[26] Rajendra Shimpi et al., "Investigation on Effects of Variation of Tool Pin Profile in a Friction Stir Welding Process by Finite Element Approach for Joining Dissimilar Materials," *Materials Today: Proceedings*, vol. 66, pp. 1361-1364, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[27] Subramani Narayanasarma, and Biju T. Kuzhiveli, "Evaluation of the Properties of POE/SiO2 Nanolubricant for an Energy-Efficient Refrigeration System – An Experimental Assessment," *Powder Technology*, vol. 356, pp. 1029-1044, 2019, [CrossRef] [Google Scholar] [Publisher Link]

[28] Rajendra shimpi, Cheruku Sandesh Kumar, and Rajnish katarane, "Friction Stir Welding Processing, Materials and its Applications," *IOP Conference Series: Materials Science and Engineering*, vol. 810, pp. 1-13, 2020. [CrossRef] [Google Scholar] [Publisher Link]