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Research Article

Effect of Titanium Dioxide Nanoparticles on Vapor Compression Refrigeration System Performance using R-410A Refrigerant and Polyolester Oil

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Abstract:
In this research, titanium dioxide nanoparticles were dispersed in polyolester oil to form a nanolubricant. The impact of this nanolubricant on the vapor compression refrigeration system performance, operating with R410A refrigerant was studied. The experimentation involved mixing different quantities of nanoparticles by mass into the POE lubricant. The quantities of TiO_2 nanoparticles used were 0.5% (1.221 g/L), and 1% (2.442 g/L) to create nanolubricant mixtures. A surfactant was added to prevent agglomeration. The refrigeration system functionality was compared using parameters such as the Coefficient of Performance (COP), refrigerating effect (RE), and compressor energy consumption. Several trial runs were conducted to obtain more accurate results and conclusions. It was observed that the refrigerating effect increased by 4.70% and 9.77% for nanoparticle concentrations of 0.5% and 1%, respectively, compared to plain lubricant oil without nanoparticles. No significant variation in compressor power consumption was observed for different nanolubricant concentrations. The COP of the system was enhanced by 4.72% and 9.47% for nanoparticle concentrations of 0.5% and 1%, respectively, compared to plain lubricant oil without nanoparticles.

Keywords: *Titanium dioxide nanoparticles, Nanolubricant, Polyolester oil, R410A refrigerant*

1. Introduction

The refrigeration industry plays a crucial role in various sectors, including food processing, pharmaceuticals, and air conditioning. With rising energy costs and environmental concerns, improving the energy efficiency of refrigeration systems has become an urgent necessity. Recent advances in nanotechnology have introduced nanoparticles into refrigerants and lubricants, resulting in promising enhancements in thermal properties and operational performance. Nano-refrigerants utilize the distinct characteristics of nanoparticles, like enhanced thermal conductivity and lower viscosity, to boost heat transfer and reduce energy usage.

This paper explores the transformative potential of nanotechnology in refrigeration, highlighting various studies that demonstrate the benefits of incorporating nanoparticles such as TiO_2. Furthermore, the implications of these findings for sustainable refrigeration practices and the necessity for continued research in this area were discussed.

In recent years, nanoparticles have attracted significant interest for their potential to improve the performance of refrigerants and lubricants. This literature review synthesizes research on the use of nanoparticles in these domains, focusing on their impact on thermal conductivity, heat transfer, and lubrication efficiency.

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The integration of nanoparticles into refrigerants has been extensively studied to improve the efficiency and performance of cooling systems**.** Jwo C. S. et al [2] investigated the advantages of replacing R-134a refrigerant and polyester lubricant with a hydrocarbon refrigerant and mineral lubricant enhanced with Al_2O_3 nanoparticles. The results indicated that optimal performance was achieved with 60% hydrocarbon refrigerant and 0.1 wt. % Al_2O_3 nanoparticles in the lubricant. With these parameters, power requirement decreased by approximately 2.4%, and the coefficient of performance (COP) improved by 4.4%. These findings demonstrated that both the hydrocarbon refrigerant and the nanoparticle-enhanced lubricant improved energy efficiency and overall performance in refrigeration systems. Jiang W. et al [3] found the thermal conductivities of CNT nanorefrigerants increased significantly with CNT volume fraction. At 1.0 vol % CNT, the thermal conductivities of four CNT-R113 nanorefrigerants rose by 82%, 104%, 43%, and 50%, respectively. These increases were greater than those seen in CNT-water nanofluids and spherical-nanoparticle-R113 nanorefrigerants with the same volume fraction. Both CNT diameter and aspect ratio affected thermal conductivity, with smaller diameters and larger aspect ratios leading to higher values. The diameter had a more significant impact than the aspect ratio.

Bobbo S. et al [4] found that nano-oils exhibited nearly the same R-134a solubility as the base oil. Adding nanoparticles (TiO_2 or SWCNH) did not significantly alter the intermolecular forces between R134a and the POE oil. This was likely due to the surface characteristics of the nanoparticles and their minimal interaction with the liquid molecules. Subramani N. et al. [5] demonstrated that a refrigeration system using a SUNISO 3GS oil mixture with alumina nanoparticles had a higher freezing capacity compared to one using POE oil. This nanolubricant led to a 25% reduction in compressor power consumption and a 33% increase in the coefficient of performance relative to conventional POE oil. Additionally, the energy enhancement factor in the evaporator was 1.53. The thermal conductivity and viscosity of Al_2O_3/R141b nanorefrigerant, with concentrations ranging from 0.5% to 2% and temperatures between 5°C and 20°C, were examined by Mahbubul I. M. et al. [7] R-141b refrigerant was mixed with Al_2O_3nanoparticles having an average diameter of 13 nm. The results showed that thermal conductivity increased with both nanoparticle concentration and temperature, while viscosity rose with higher volume fractions but decreased with increasing temperature. At a 2% concentration nanoparticle, the maximum value of thermal conductivity and viscosity were 1.626 and 179 multiples higher than that of the base fluid, respectively.

An experimental investigation was conducted to study the effect of CuO nanoparticles on the flow boiling of R600a at low vapor qualities by Baqeri, S. et al [8]. Polyolester oil was used to disperse the nanoparticles into the refrigerant. It was observed that the coefficient of heat transfer increased with the addition of CuO nanoparticles, reaching its peak at a 2% mass fraction. Enhancements in the coefficient of heat transfer was 4.56%at 0.5%, 18.25%at 1%, and 32.59%at 1.5% mass fractions, compared with a 1% nanorefrigerants mixture by mass.At a 5% mass fraction of CuO nanoparticles, however, the coefficient of heat transfer decreased by 7.94% relative to the baseline. The study conducted by Mahbubul, I. M. et al [10] investigated the impact of adding Al_2O_3 nanoparticles to R-134a refrigerant. The study was conducted by varying the temperatures from 283 to 308 K. Results showed that thermal conductivity, dynamic viscosity, and density of the Al_2O_3/R-134a nanorefrigerant increased by about 28.58%, 13.68%, and 11%, respectively, compared to pure R-134a refrigerant. However, its specific heat was slightly lower. The nanorefrigerant achieved a 15% improvement in COP for thermal conductivity, 3.2% for density, and 2.6% for specific heat, indicating that nanoparticle addition can enhance refrigeration and air-conditioning system performance. Jiang-feng Lou et al [11] experimentally investigated the preparation and characterization of graphite nanolubricants. The efficiency of a household refrigerator with graphite nanolubricants at mass fractions of 0%, 0.05%, 0.1%, 0.2%, and 0.5% was assessed.The use of graphite nanolubricants resulted in lower evaporator temperatures, condenser temperatures, discharge pressure, suction pressure, and compressor temperature. Additionally, at a 0.1% mass fraction, the pull-down time was reduced by 15.22% and energy usage was reduced by4.55%.

An experimental study by Akhavan-Behabadi, M. A. et al [12] was conducted. The thermal behavior of nano-refrigerant flows in a horizontal plain tube using pure refrigerant (R-600a), a refrigerant/oil blend (R-600a/oil), and a refrigerant/lubricant/nanoparticle mixture (R-600a/oil/CuO) was studied. The experiments varied mass fluxes (154.8 to 265.4 kg/m²/s), qualities of vapor (10% to 80%), heat fluxes (17 to 20 kW/m²), and condensation pressures (5.1 to 6.2 bar). Results showed that adding nanoparticles increased the heat transfer coefficient, with a 1.5% nanoparticle mass fraction enhancing transfer of heat by 83% compared to pure refrigerant. The improvement was more significant at lower mass fluxes. Experiments of Zhelezny, V. P. et al [15] showed that adding Al_2O_3 and TiO_2 nanoparticles to an R600a/mineral oil solution reduced surface tension and increased solubility and viscosity. These effects depend on both the concentration of the nanoparticles and the temperature. The study of Helvaci, H.U., and Khan, Z.A. [16] evaluated four nanofluids such as Al_2O_3, CuO, SiO_2, and MgO nanoparticles dispersed in pure HFE

7000, with particle volumetric concentrations of 0%, 1%, 4%, and 6% and Reynolds numbers of 400, 800, 1200, and 1600. The highest average increase in the heat transfer coefficient, 17.5%, was observed with MgO-HFE 7000, while Al_2O_3-HFE 7000 exhibited a 16.9% increase, CuO-HFE 7000 showed a 15.1% rise, and SiO_2-HFE 7000 demonstrated a 14.6% improvement at a 6% concentration. However, this improvement in heat transfer was accompanied by a pressure drop increase of 9.3% to 28.2%. Additionally, the overall entropy generation reduced with increased Reynolds numbers and particle concentrations for all nanofluids. Thus, using HFE 7000-based nanofluids containing Al_2O_3, MgO, SiO_2, and CuO nanoparticles, enhances thermal performance when the flow was laminar. Adelekan, D. S. et al [23] demonstrated that graphene-based nanolubricants additives significantly improved the Iso-butane driven domestic refrigerator's energetic performance only with a 40g mass charge of R600a. All nanolubricant mixtures achieved at least -3°C cabinet temperature during steady conditions, with the exception of 70g mass charge of R-600a and a 0 gram/Liter blend. The VCR functionality showed improvement as concentrations of grapheme increases solely at a 40gram mass charge of R-600a. Power per Ton of Refrigeration value for the graphene-based nanolubricants was lower at 40g mass charge of R-600a.Power per Ton of Refrigeration value for the graphene-based nanolubricants were higher at 50, 60, and 70g mass charge of R-600a compared to the non-blended lubricant, with a value lying between 4.59 to 5.22. Furthermore, power consumption increased with the chosen graphene-based nanolubricants at a 40g mass charge of R-600a but decreased at mass charges of 50g, 60g, and 70g compared to the non-blended lubricant.

Adelekan, D. S. et al [24] investigated the efficiency of the household refrigerator, utilizing a safe charge of 40g of R600a refrigerant and different concentrations of TiO_2 nanolubricants. Their findings showed improvements in energetic and cooling performance with the selected concentrations. The mean power consumption was about 6.2% lower with 0.2 gram/Liter lubricants compared to 0 gram/Liter, but increased by 8.87% with 0.4 gram/Liter and 0.92% with 0.6 gram/Liter lubricants. Nanolubricants containing resulted in higher mean Power per Ton of Refrigeration values compared to the plain lubricant. However, the mean discharge temperatures with these nanolubricants were approximately 6-24% higher than with the baseline lubricant. Additionally, the coefficient of performance with TiO_2-based nanolubricants was lower than with 0 g/L lubricants, by about 1.33-9.33%.
From the literature, it is evident that there is limited research on the use of nanolubricants in modern refrigerants like R-410A and R-407C, which were developed as alternatives to R-22, a refrigerant banned due to its ozone-depleting properties. While nanolubricants, which incorporate nanoparticles to enhance thermal conductivity, viscosity, and friction reduction, have been studied with older refrigerants, their potential with newer, environmentally friendly alternatives remains underexplored. These nanolubricants could improve the efficiency of refrigeration systems by enhancing heat transfer, reducing wear, and extending system lifespan, particularly with refrigerants that have different thermodynamic properties.

However, challenges such as ensuring compatibility with these refrigerants, assessing long-term stability, and evaluating their cost-effectiveness in commercial applications need to be addressed. With the growing need for energy-efficient and sustainable cooling technologies, further research into the integration of nanolubricants with refrigerants like R-410A and R-407C is crucial to optimize system performance and minimize environmental impact.

2. Experimental Setup

The vapor compression cycle setup was assembled using components specifically designed for the R-410A refrigerant. The experimental setup resembles a split AC system. Five temperature sensors (from Aptech Deals Mini LCD TPM-14 digital thermometer sensor) were installed at different locations on the refrigerant lines and inside the wooden cabin. These sensors enable real-time monitoring, allowing for precise analysis of temperature variations at key points within the system. Thermocouples were attached on the outer surface of the refrigerant carrying pipe. The thermocouples were tightly attached and covered to minimize the error in temperature measurement. A closed system is a crucial design consideration for any HVAC device. A wooden cabinet with dimensions of 1000 mm x 800 mm x 800 mm was used as the enclosed space, with 12 mm. thick foam used as insulation material. Insulation material provides the resistance to heat flow from outside which maintains the temperature and humidity in the wooden cabin. The setup featured a hermetically sealed 12000 BTU GMCC TOSHIBA rotary air conditioner compressor. The evaporator coil was made of copper tubing with radial fins to increase surface area. The evaporator coil tube had an internal diameter of 6.3 mm and an external diameter of 7 mm. The condenser was a thin coil of copper tubing located at the back of the setup and was cooled by forced convection using an external fan. The condenser coil had an inside diameter of 5.8 mm and an outside diameter of 6.4 mm. The capillary tube, composed of several turns of thin copper coil, was part of the setup. A fan was installed behind the condenser to assist with heat removal. In addition, two pressure gauges were mounted at the inlet and outlet of the compressor to measure suction and discharge pressures. The pressure gauges were double manifold gauges. The compressor power consumption was measured by using voltmeter and ammeter. Digital volt ampere meter (manufactured by TRUENX) was used.

Table 1: Uncertainty and measurement range of instruments

Sr. No.	Characteristics	Range	Uncertainty
1	Pressure	-1 to 55 bar	± 1.6 %
2	Temperature	-50 to 70 ºC	± 1 ºC
3	Voltage	130 V to 350 V	± 0.5 %
4	Current	1 Amp. to 45 Amp.	± 0.5 %

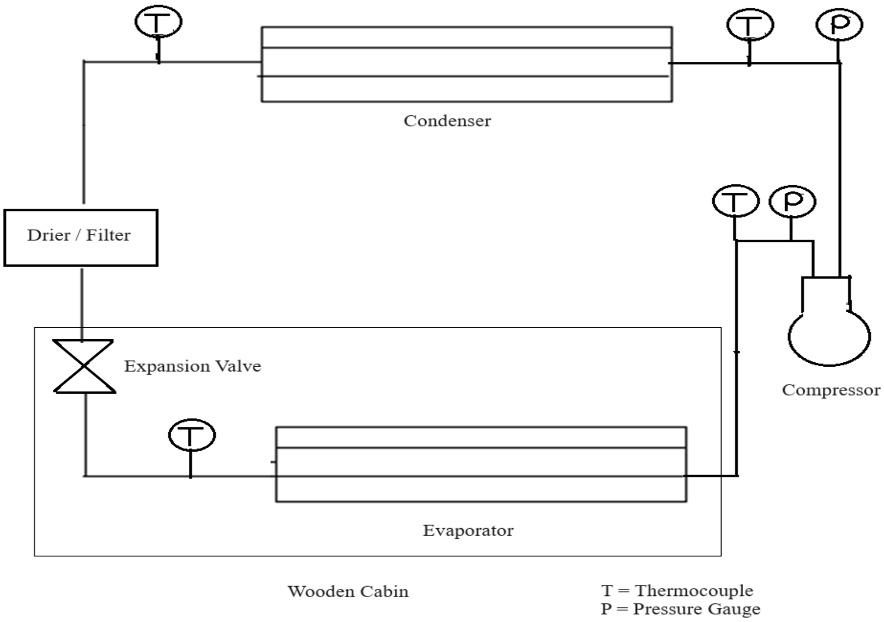

Fig. 1. Set up Block diagram of VCR system

Fig. 2. Experimental Set Up

3. Nanolubricant Preparation

Nanolubricant was prepared by mixing titanium dioxide nanoparticles into polyolester oil. The nanoparticles, purchased from Techinstro Industries, Nagpur, Maharashtra, India, had a size range of 30-80 nm and a purity of 99.9%. Their properties are listed in Table 1.

Table 2: Properties of Nanoparticle

Specifications	Values
Purity	99.9 %
Average Particle Size	30-80 nm
Specific Surface Area	150 m^2/g
Molecular Weight	79.8658 g/mol
Molecular Formula	TiO_2
Melting Point	1843 °C
Bulk Density	4.23 g / cm^3
Physical Form	Powder
Morphology	Near Spherical
Color	White

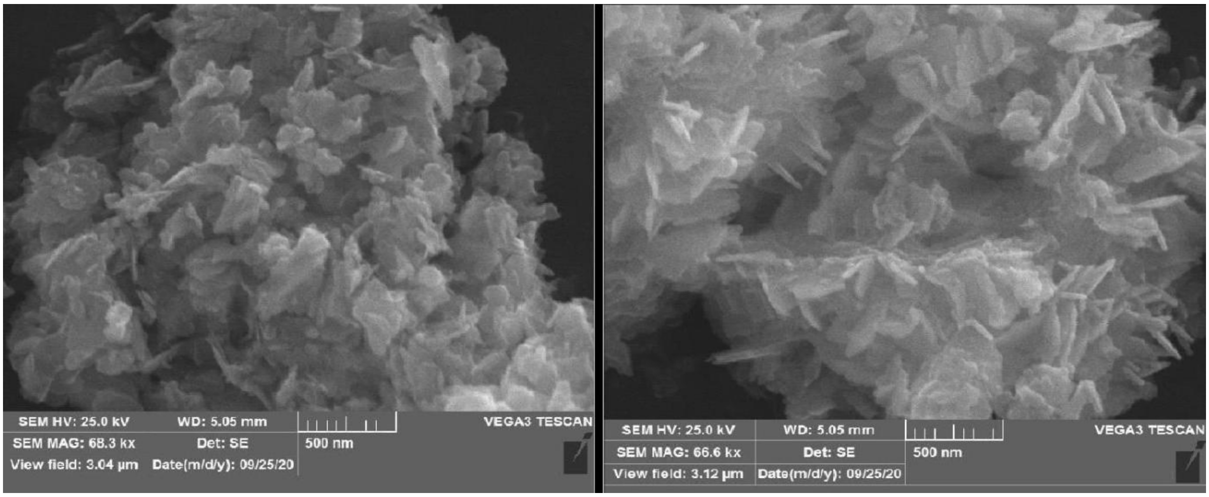

Fig. 3. SEM Images of Titanium Dioxide Nanoparticles

Emkarate RL 68H is a synthetic polyolester (POE) lubricant formulated specifically for refrigeration and air-conditioning compressors using HFC refrigerants, such as R-410A. It is an ISO VG 68 lubricant designed for optimal performance in these systems.

Table 3: RL68H Polyolester oil properties

Properties	Method	Value
Viscosity @ 40 °C (cSt)	ASTM D445	66.6
Viscosity @ 100 °C (cSt)	ASTM D445	9.4
Viscosity Index	ASTM D2270	120
Pour Point (°C)	ASTM D97	-39
Density @ 20 °C (g/ml)	ASTM D1298	0.977
Flash Point COC (°C)	ASTM D92	270
Acid Value (mg KOH/g)	ASTM D974	<0.05

Nanolubricant was prepared by using two step method. The mass of nanoparticle to be blended in lubricant is calculated by using the relation as below;

$$w = \frac{m_{NP}}{m_{NP} + m_{oil}}$$

Here, w = percentage of nanoparticles to be mixed in lubricant;
m_{NP} = Mass of nanoparticles;
m_{oil}= Mass of lubricant.

High speed Homogenizer was used as an equipment for nanolubricant preparation. High Speed Homogenizer was a laboratory instrument or industrial equipment designed for rapid and vigorous mixing, emulsification, and homogenization of samples. It was an essential tool for achieving uniform mixtures, improving sample consistency, and enhancing product quality through rapid and efficient processing.

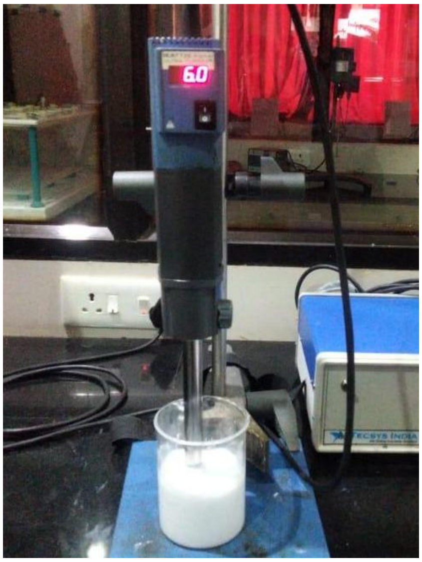

Fig. 4. High Speed Homogenizer

After preparing the nanofluid using a two-step method, the nanomaterials tended to agglomerate, which could lead to sedimentation, clogging of channels, and a decrease in thermal conductivity. To prevent sedimentation and ensure uniform suspension of the nanoparticles throughout the POE oil, a surfactant was introduced into the mixture of the POE oil and nanoparticles before blending. The surfactant, Oleic Acid, was used in a 1:1 mass ratio relative to the nanoparticles. [20] Oleic Acid reduces the surface tension of the POE oil, enhancing its spreading and wetting properties, and thereby achieving a uniform dispersion of TiO_2 within the base fluid. A High-Speed Homogenizer, operating at 6000 rpm, was employed for the nanolubricant preparation. This device uses rotor-stator technology or other mechanical means to generate intense shear forces, breaking down particles and blending substances effectively. The homogenizer was used for 30 minutes to ensure a consistent mixture and improve sample quality through rapid and efficient processing. The mixture was then observed for uniform distribution of nanoparticles in the lubricant.

Fig. 5. POE oil before and after blending

4. Calculation

Multiple tests were performed on the experimental setup to identify the setup performance accurately. The observations were recorded by keeping the initial conditions same. The air side values were considered for calculating the refrigeration effect. The refrigeration effect was equal to the sensible heat removed from the air in the cabin.

The mass of air in the cabin was calculated by considering the volume of the cabin.

$$m_a = \rho \times V_a$$

m_a = mass of air in cabin in kg,
ρ = Density of air at standard conditions Kg/ m^3,
V_a = Volume of cabin in m^3,

The refrigeration effect or sensible heat removed from the air was given as;

$$Re = m_a \times c_{pa} \times (T_f - T_i)$$

c_{pa} = Specific Heat of air;
$(T_f - T_i)$ = Decrease in temperature of air in the cabin.

Power consumed by compressor was calculated by using the readings of voltmeter and ammeter. The Power consumed by compressor of VCR System.

$$P = V \times I$$

V = Voltage recorded by voltmeter in volts;
I = Current consumed by the compressor measured by Ammeter in Amperes.
The coefficient of performance of VCR system could be calculated by using the formula;

$$C.O.P. = \frac{Re}{P}$$

5. Result and Discussion

Multiple tests were performed on the experimental setup to identify the setup performance accurately. The observations were recorded by keeping the initial conditions same.

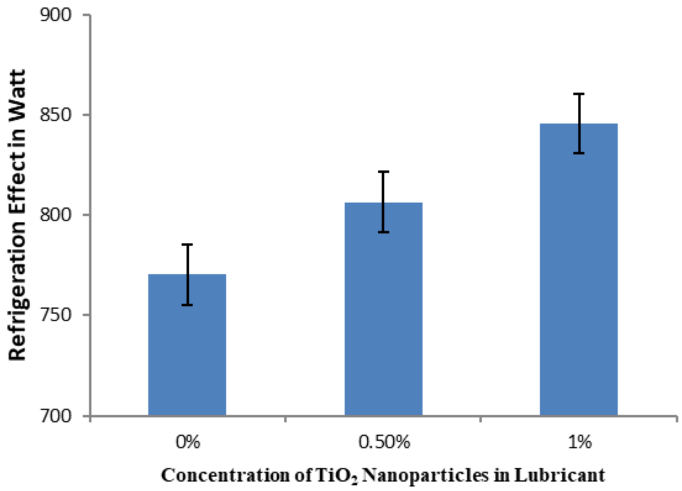

Fig. 6. Variation in Refrigeration effect (in Watt) with respect to Titanium Dioxide nanoparticle concentration

Fig 6 shows 0.5% TiO_2 nanoparticles concentration shows a 4.69% increase over without TiO_2 nanoparticles. 1% TiO_2 nanoparticles concentration shows a 9.61% increase over the baseline. This more precise analysis highlights the systematic improvement in refrigeration effect with increasing TiO_2 nanoparticle concentration, showing a consistent, measurable benefit within the tested range.

The improved refrigeration performance with TiO_2 nanoparticles is due to enhanced thermal conductivity, increased heat transfer surface area, and micro-convection effects within the refrigerant. Xiang Y. et al [25] found the improvement in thermal conductivity of 8.05%. The high thermal conductivity of TiO_2 enables faster heat transfer, while the nanoparticles' presence disrupts the thermal boundary layer, reducing resistance to heat flow. Additionally, the random motion of nanoparticles (Brownian motion) creates micro-scale eddies that promote better heat distribution, and slight increases in specific heat capacity allow the fluid to absorb more heat efficiently. Together, these effects result in a consistent, measurable improvement in cooling performance with increasing TiO_2 concentration.

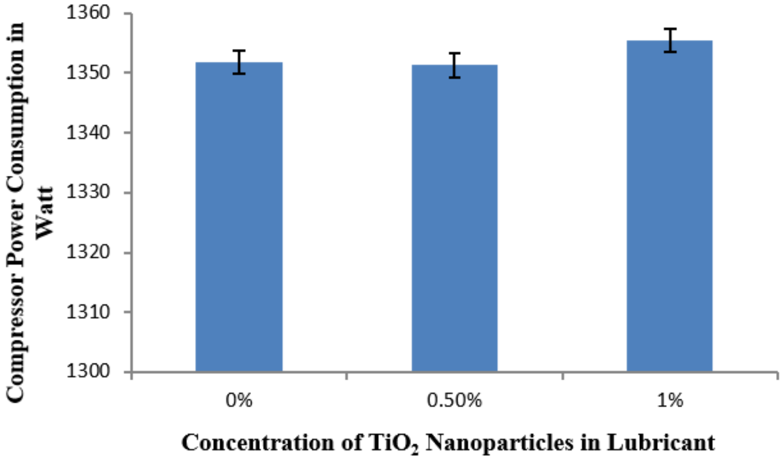

Fig. 7. Variation in Compressor Power Consumption (in Watt) with respect to Titanium Dioxide nanoparticle concentration

Fig 7 shows that the addition of TiO_2 nanoparticles has a very minor, non-linear effect on compressor power consumption within the tested concentration range. The changes are so small that they may not be statistically or practically significant without further statistical analysis.

The minor, non-linear effect of TiO_2 nanoparticles on compressor power consumption can be explained by the balance between two opposing physical factors: viscosity and thermal conductivity. Adding nanoparticles slightly increases the fluid's viscosity, which can raise the compressor's workload by creating additional resistance to flow. KrishnaSabareesh et al [6] was found an increase in viscosity of 19%. However, this effect is minimal at low nanoparticle concentrations, like those tested, and is counterbalanced by the improved thermal conductivity of the nanofluid. Enhanced thermal conductivity leads to more efficient heat transfer, reducing the required cooling load and thereby offsetting potential increases in power consumption. The net effect on compressor power remains small and non-linear, as the changes in viscosity and thermal conductivity are not substantial enough to impact power demand significantly. Thus, the effect is neither large enough to be practically significant nor consistent, leading to a non-linear and negligible impact on power consumption.

Fig 8 illustrates the Coefficient of Performance (COP) for different concentrations of TiO_2 nanoparticles. From 0% to 0.5% TiO_2 nanoparticles concentration, there is an increase of approximately 0.0270 (4.73% improvement) in COP. From 0.5% to 1% TiO_2 nanoparticles concentration there is an increase of about 0.0265 (4.43% improvement) in COP. From 0% to 1% % TiO_2 nanoparticles concentration, a total increase of 0.0535 (9.38% improvement) is observed. This figure demonstrates that adding TiO_2 nanoparticles has a substantial and positive effect on the Coefficient of Performance. The improvement in COP without a significant increase in energy consumption (as seen in the previous graph) indicates that TiO_2 nanoparticles are enhancing the system's efficiency.

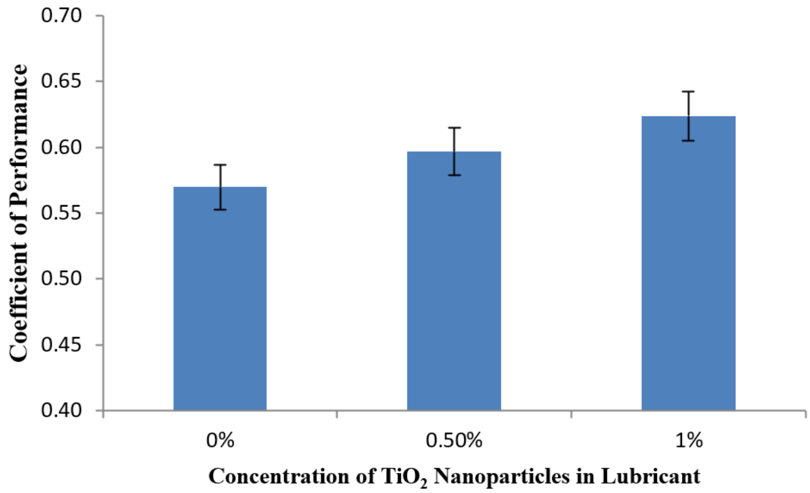

Fig. 8. Variation in Coefficient of Performance with respect to Titanium Dioxide nanoparticle concentration

The observed increase in the Coefficient of Performance (COP) with TiO_2 nanoparticles is primarily due to improved thermal properties and heat transfer efficiency in the refrigerant [32]. TiO_2 nanoparticles have high thermal conductivity, which enhances the refrigerant's ability to absorb and release heat more effectively within the evaporator and condenser. This improved heat transfer lowers the temperature differential needed to achieve the desired cooling effect, reducing the work required from the compressor [19]. Additionally, the micro-convective effects created by the Brownian motion of the nanoparticles enhances fluid mixing, further improving heat distribution within the refrigerant. These effects allow the refrigeration cycle to operate more efficiently, increasing the COP without a proportional increase in compressor energy consumption. Consequently, adding TiO_2 nanoparticles improves the cooling capacity of the system, demonstrating a net positive impact on performance.

6. Conclusion

- The addition of TiO_2 nanoparticles enhances the cooling effect. The 1% TiO_2 nanoparticles concentration shows the most rapid temperature decrease over time, followed by 0.5% TiO_2 nanoparticles, while the system without TiO_2 nanoparticles cools the slowest.
- There is no clear trend in energy consumption across the TiO_2 nanoparticles at different TiO_2nanoparticle concentrations. The energy consumption fluctuates over time for all three conditions, with no consistent advantage for any particular concentration.
- The refrigeration effect increases with higher TiO_2 nanoparticles concentrations. The 1% TiO_2 nanoparticles solution demonstrates the highest refrigeration effect, followed by 0.5% TiO_2 nanoparticles, while the system without TiO_2 nanoparticles has the lowest effect.
- The COP is generally higher for systems with TiO_2 nanoparticles. The 1% TiO_2 nanoparticles concentration shows the highest COP, followed closely by 0.5% TiO_2 nanoparticles, while the system without TiO_2 nanoparticles has the lowest COP. The addition of TiO_2 nanoparticles, particularly at 1% concentration, appears to enhance the cooling capability and performance of refrigeration system. This is evidenced by faster temperature reduction, higher refrigeration effect, and better coefficient of performance. These conclusions suggest that incorporating TiO_2nanoparticles, especially at 1% concentration, can enhance the overall efficiency of the refrigeration system, despite the lack of clear energy consumption benefits.

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