



A Review on the Effect of Metal Oxide Nanoparticles on the Performance of Refrigeration Systems

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ABSTRACT

The use of nanoparticles in refrigeration systems has gained attention for their potential to significantly improve energy efficiency and system performance across a range of applications. These nanoparticles are often referred to as nanorefrigerants. This paper explores recent research works that demonstrate how nanoparticles like titanium dioxide (TiO₂), aluminum oxide (Al₂O₃), and copper oxide (CuO) can result in marked reductions in energy consumption and notable improvements in the coefficient of performance. Key breakthroughs include enhanced heat transfer efficiency, increased thermal conductivity, and reduced frictional losses, all of which contribute to more efficient refrigeration systems. These advancements are particularly valuable in industries such as food processing, where optimizing energy use and maintaining temperature control are essential. However, there are challenges, including the potential for higher pressure drops within the system. Nevertheless, the advantages of using nanotechnology in refrigeration systems emphasize the necessity for continued research to optimize nanoparticle formulations and address the challenges, ensuring that nanorefrigerants can be fully utilized to improve sustainability and performance in refrigeration applications.

Keywords: Nanorefrigerants; Coefficient of performance; Nanolubricant; Metallic oxide nanoparticles.

1. INTRODUCTION

The refrigeration industry is essential to multiple sectors, including food processing, pharmaceuticals, and air conditioning. In the past few years, the use of Heating, Ventilation and Air Conditioning (HVAC) equipment has seen a dramatic rise in commercial, domestic and industrial sector, due to high summer temperatures, high humidity levels and changing lifestyle requirements. As far as the Indian scenario is concerned, the use of refrigeration and air conditioning equipment is increasing in household applications as well as the industrial sectors *viz.*, the cold storages and pharmaceutical industries. According to the Indian Society of Heating, Refrigerating and Air conditioning Engineers, the Air-Conditioner (AC) market has been growing faster than other sectors, at an average of 18-20% over the last decade. The penetration of room ACs in Indian household is found to increase at a very rapid rate, suggesting that there is a considerable rise expected due to changes in climatic conditions. According to International Energy Agency, the largest growth in Air Conditioning units is projected in India as depicted in Fig. 1.

As energy costs continue to rise and environmental concerns grow, there is a pressing need to enhance the energy efficiency of refrigeration systems. Current research aimed at enhancing the performance of HVAC systems focuses on techniques to improve heat

transfer rates, such as the use of nanoparticles, environmentally friendly refrigerants, and modifications to mechanical systems (e.g., variable refrigerant flow) (Hernandez and Fumo, 2020) and electrical components (e.g., inverter-based air conditioners).

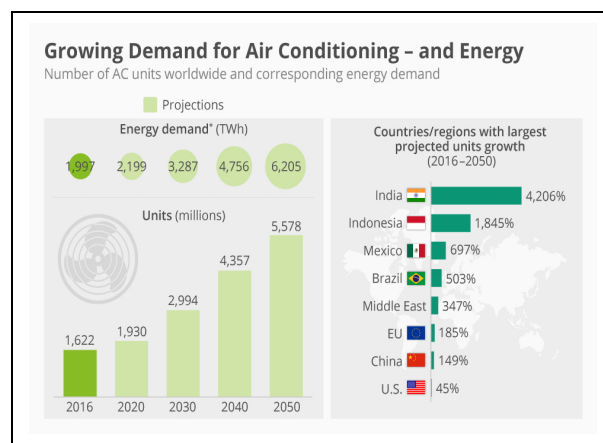


Fig. 1: Projected growth of AC and energy

Recent developments in nanotechnology have led to the incorporation of nanoparticles in refrigerants and lubricants, showing significant improvements in thermal characteristics and operational efficiency. Nanorefrigerants take advantage of the distinct properties of nanoparticles, like enhanced thermal conductivity and reduced viscosity, to boost heat transfer and lower energy usage. This paper examines the transformative impact of

nanotechnology on refrigeration, showcasing various studies that highlight the advantages of using nanoparticles such as TiO_2 , Al_2O_3 , and CuO . Furthermore, the implications of these findings for sustainable refrigeration practices and the necessity for continued research in this area is discussed.

2. NANOFLUID PREPARATION

Nanofluids are prepared by dispersing nanoparticles within a base fluid. Achieving stable dispersion is essential for nanofluid applications, so surfactants are added to enhance stability.

Additionally, modifying the surface of the nanoparticles and applying strong forces to break up nanoparticle clusters can further improve nanofluid stability. There are two primary approaches for preparing nanofluids: single-step method and two-step physical method.

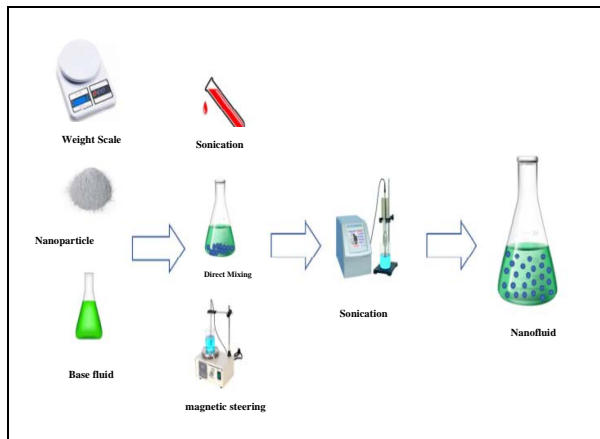


Fig. 2: Twostep process for nanolubricant preparation (Siddique *et al.* 2024)

Two-step method shown in Fig.2 is the most cost-effective approach for producing nanofluids on a large scale. In this process, nanoparticles are synthesized using various techniques and then dispersed into a base fluid to create the desired nanofluid. In a vapor compression refrigeration system used in refrigerators and air conditioners, nanoparticles are added to the lubricants used in the compressor. The resulting mixture is known as nanolubricant. As the nanolubricant comes into contact with the refrigerant, the nanoparticles disperse and mix with the refrigerant, forming a nanorefrigerant, which then flows throughout the entire refrigeration system. This method is economical and suitable for large-scale production. However, a major limitation is the tendency of nanoparticles to aggregate, leading to instability. To counteract this, surfactants are often added to improve stability. This commercially viable technique is widely favoured by researchers for nanofluid preparation in research applications.

3. EFFECT OF Al_2O_3 NANOPARTICLES

The integration of Al_2O_3 (alumina) nanoparticles into refrigeration systems has consistently shown impressive performance improvements across a variety of system configurations and refrigerant types, underlining the significant potential of this technology to enhance the efficiency of modern cooling applications. Through various studies, researchers have identified substantial gains in coefficient of performance (COP), reductions in power consumption, and other operational efficiencies, even at remarkably low concentrations of Al_2O_3 nanoparticles.

In domestic refrigeration applications, Al_2O_3 has been shown to reduce energy consumption by 2.69%, which, although a modest figure, is considerable given the minimal concentration of nanoparticles used (Sarrafzadeh and Saidur, 2021). Likewise, vapor compression systems, a fundamental component in both residential and commercial cooling, have benefited from significant improvements, with COP increases of up to 37.2% and reduction in power consumption by 28.7% (Joshi *et al.* 2021). These studies indicate that even minor amounts of Al_2O_3 nanoparticles (0.01–0.02% by weight) can enhance performance, yielding COP gains ranging from 3.33% to 12% and the thermal conductivity increases by 11.5% and 14.2%, which is remarkable given the low nanoparticle loading (Mahdi *et al.* 2017).

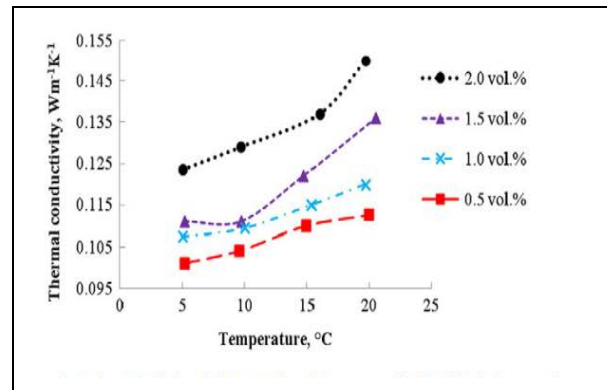


Fig. 3: Variation of thermal conductivity of $\text{Al}_2\text{O}_3/\text{R141b}$ nanorefrigerant (Mahbubul *et al.* 2013)

Some of the most outstanding improvements with Al_2O_3 have been achieved in diffusion absorption refrigeration systems (DARS). In DARS configurations, Al_2O_3 nanoparticles led to a remarkable 55.56% increase in COP, which was also accompanied by a significant 51.72% reduction in the circulation ratio, a critical factor influencing system efficiency (Sozen *et al.* 2015). In systems using R-32 refrigerant, the introduction of Al_2O_3 nanoparticles achieved a COP improvement of 46.14% and reduced power consumption by an impressive 31.59%, making it a valuable option for reducing energy demands in conventional refrigeration systems (Dilawar *et al.* 2022).

Another important development is the use of Al_2O_3 in nanolubricants, which combine nanoparticles with specific lubricating oils to optimize the system's mechanical performance. For instance, nanolubricants incorporating Al_2O_3 with polyolester (POE) oil demonstrated a COP increase of 19–22%, alongside a 27.73% reduction in energy consumption (Haque *et al.* 2016). This dual benefit, enhancing COP and reducing energy use, shows the potential of nanolubricants to further optimize refrigeration systems, especially in applications that rely on highly efficient compressors.

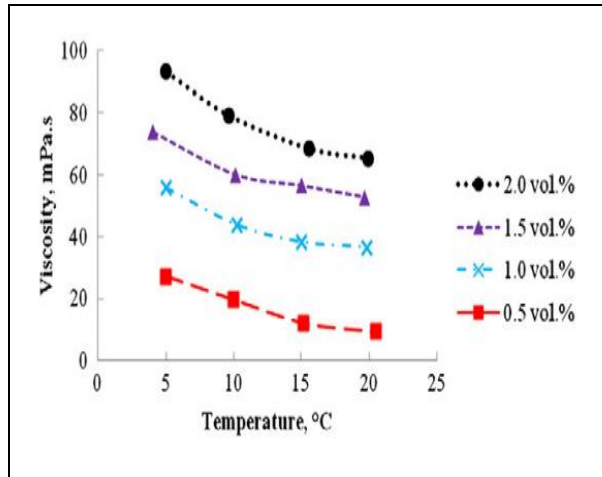


Fig. 4: Variation of viscosity of $\text{Al}_2\text{O}_3/\text{R141b}$ nanorefrigerant (Mahbubul *et al.* 2013)

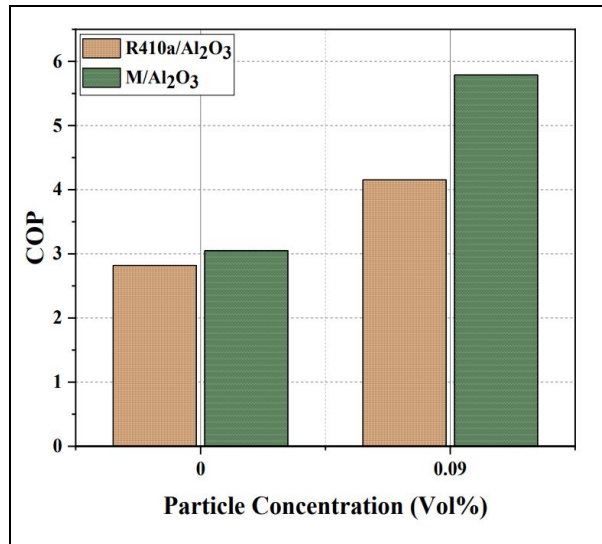


Fig.5: Variation of COP of $\text{Al}_2\text{O}_3/\text{R410A}$ nanorefrigerant (Dilawar *et al.* 2022)

Recently, studies have explored the use of Al_2O_3 nanoparticles in R-410A refrigerant systems, where results have been noteworthy. Power savings of up to 47.2 % were observed, emphasizing the transformative potential of Al_2O_3 in high-efficiency systems (Dilawar *et al.* 2022).

In hybrid systems, particularly those using R134a refrigerant with polyalkylene glycol (PAG) oil and Al_2O_3 , enhancements were also significant; these systems achieved a 6.5% improvement in COP through improved subcooling at the condenser exit (Nair *et al.* 2020). Such improvements in hybrid configurations highlight adaptability and effectiveness of Al_2O_3 across diverse refrigeration setups.

Notable results for Al_2O_3 nanoparticles in refrigeration systems include a significant (96.23%) improvement in thermal conductivity when used with R-134a refrigerant (Habib *et al.* 2021). In systems with R-141b, Al_2O_3 nanoparticles also enhanced multiple properties: density increased by 11.54%, viscosity by 12.63%, and thermal conductivity by 28.88% (Alawi *et al.* 2019). These improvements underscore the potential of Al_2O_3 nanoparticles to boost thermophysical properties in various refrigerant applications.

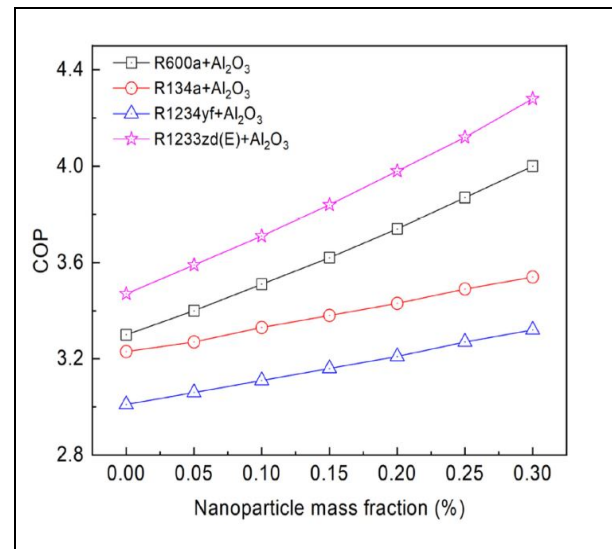


Fig. 6: Variation of COP due to Al_2O_3 nanoparticle in different refrigerants (Li *et al.* 2022)

The performance of four Al_2O_3 nanorefrigerants and their respective pure fluids (R600a, R134a, R1234yf, and R1233zd (E)) was assessed in a vapor-compression refrigeration cycle. The enthalpy of the nanorefrigerant within the cycle was estimated using a prediction method based on the density of the nanorefrigerant. A numerical model was created for thermodynamic analysis, and the results revealed that the addition of nanoparticles to the pure refrigerant reduced compressor power consumption and improved heat transfer within heat exchangers, cooling capacity and overall performance of the refrigeration system. The highest improvement of 23.24% in COP was observed with the R1233zd (E) + Al_2O_3 nanorefrigerant, while R600a+ Al_2O_3 showed 21.07 % improvement, R134a + Al_2O_3 showed 9.77% and R1234yf + Al_2O_3 showed 10.30% improvement in COP as depicted in Fig. 6. (Li and Lu, 2022)

Table 1. Effect of Al₂O₃ nanoparticles in refrigeration system

Source	Refrigerant	Observed Effect
Jwo <i>et al.</i> (2009)	R134a	2.4% reduction in power consumption, 4.4% increase in COP
Mahbubul <i>et al.</i> (2013)	R141b	Increased thermal conductivity, dynamic viscosity, and density compared to base refrigerants
Mahbubul <i>et al.</i> (2015)	R134a	Thermal conductivity, dynamic viscosity, and density of nanorefrigerant increased about 28.58%, 13.68%, and 11%, respectively
Hernandez <i>et al.</i> (2016)	R134a	Selected for high thermal efficiency; thermal characteristics improved at 1 vol% and 5 vol%, nanoparticle size impact minimal
Hussain <i>et al.</i> (2018)	R-134a	COP enhancements of 25.7%, 17.46%, and 11.74%
Soliman <i>et al.</i> (2019)	R-134a	22.5% performance enhancement, 10% reduction in energy consumption
Alawi <i>et al.</i> (2019)	R-141b	Increased density, dynamic viscosity, and thermal conductivity; COP improvement
Ahmed <i>et al.</i> (2019)	R134a	Cooling performance improvement and power utilization reduction
Nair <i>et al.</i> (2020)	R134a	COP increase of up to 6.5% due to higher subcooling at condenser exit
Joshi <i>et al.</i> (2021)	R134a and R600a	Improved performance, reduced power consumption, lowered evaporator pressure
Sarrafzadeh and Saidur, (2021)	R-134a	Reduced energy consumption, increased evaporator temperature gradient
Habib <i>et al.</i> (2021)	R-134a	Thermal conductivity increases by 96.23% at 0.04 volume concentration
Li <i>et al.</i> (2022)	R1233zd	COP improvement exceeding 20% at 0.30% nanoparticle mass fraction
Dilawar, <i>et al.</i> (2022)	R410A	Increased performance and power savings
Dilawar, <i>et al.</i> (2022)	R-32	46.14% COP improvement, 31.59% power savings

The research on Al₂O₃ nanoparticles in refrigeration applications spans several decades, with early studies laying the groundwork for understanding the benefits of nanoparticle integration. More recent analyses provide comprehensive evaluations of performance gains across systems. Overall, the consistent positive outcomes across a broad spectrum of

refrigeration technologies, ranging from small domestic units to large commercial systems demonstrate the robust potential of Al₂O₃ nanoparticles to drive substantial improvements in energy efficiency, reduce operational costs, and support the global transition towards more sustainable cooling solutions.

4. EFFECT OF CuO NANOPARTICLES

Extensive research on CuO nanoparticles in refrigeration systems has consistently shown that they provide substantial performance improvements across various applications, demonstrating their versatility and efficacy. When incorporated into R404a refrigeration systems, CuO nanoparticles achieved a notable COP of 3.97, alongside a refrigerating effect of 119.40 kJ/kg-K, indicating a significant boost in system efficiency (Sivakumar and Tanveer, 2017). This enhancement is especially promising for commercial refrigeration systems where R404a is commonly used, showing how CuO nanoparticles can effectively optimize cooling performance.

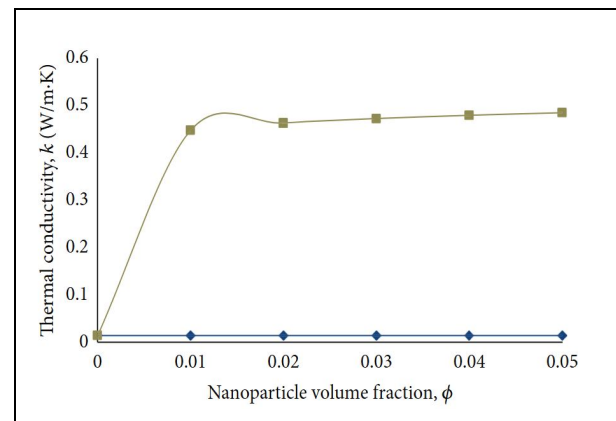


Fig. 7: Variation in thermal conductivity of CuO/R-134a nanorefrigerant (Fadhilah *et al.* 2014)

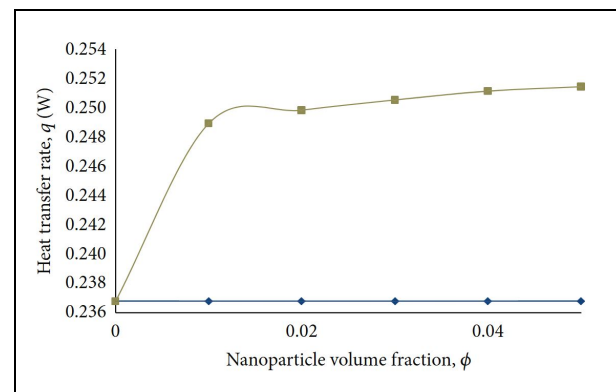


Fig. 8: Variation in thermal heat transfer rate of CuO/R-134a nanorefrigerant (Fadhilah *et al.* 2014)

In LPG-based cycles, the introduction of CuO nanoparticles yielded a remarkable 46% improvement in

COP, significantly increasing overall system efficiency. Moreover, the energy consumption of the compressor was reduced by 7%, highlighting the potential of CuO nanoparticles to contribute to energy savings, which is crucial in applications where LPG serves as a refrigerant (Kumar *et al.* 2018). These results are highly relevant as LPG-based refrigeration gains popularity due to its environmentally friendly properties.

Table 2. Effect of CuO nanoparticles in refrigeration system

Source	Refrigerant	Observed Effect
Fadilah, <i>et al.</i> (2014)	R-134a	Thermal conductivity in range of 3.53–8.38% up to 5% vol. fraction.
Sivakumar and Tanveer, (2017)	R404a	COP of 3.97 and refrigerating effect of 119.40 kJ/kg-K, eco-friendly potential
Kumar <i>et al.</i> (2018)	LPG-based cycles	COP improved by 46%, compressor energy consumption reduced by 7%
Manikanden <i>et al.</i> (2019)	R290	COP of silver-doped nano-cupric oxide increased up to 29%. Power consumption is found to reduce up to 28%
Vithya <i>et al.</i> (2020)	R-134a	COP improved by 45% for 0.3% CuO blending.
Mohamed <i>et al.</i> (2022)	R-134a	COP improved by 25%
Pipewala <i>et al.</i> (2024)	R600a	The energy consumption is reduced by 4 % and 8.2 %, with lower concentrations at 27°C and 38°C, res.

Broadly across refrigeration systems, CuO nanoparticles have led to an average coefficient of performance improvement of 25% largely attributed to increase in thermal conductivity within the system (Mohamed *et al.* 2022). This reduction in internal friction not only boosts cooling efficiency but also supports the longevity and durability of the system by decreasing wear on components. This friction reduction benefit was consistent in various applications, emphasizing CuO's capability to improve operational stability and extend the service life of refrigeration systems.

When the volume fraction of CuO nanoparticles is increased by 1%, the thermal conductivity improves by approximately 3.53–8.38%, reaching a maximum of 5% volume fraction as shown in Fig. 7. Similarly, the viscosity of the nanorefrigerant shows a significant increase, about 44.45% higher than that of the conventional refrigerant at just 1% nanoparticle volume fraction. Additionally, the heat transfer rate for a tube using nanorefrigerant with a 5% volume fraction sees an improvement of around 1% as shown in Fig. 8 (Fadhilah *et al.* 2014). These metrics are significant, especially for

systems that rely on optimized evaporator performance to maximize cooling output. By enhancing evaporator capacity and COP while simultaneously reducing energy consumption, CuO nanoparticles offer a multi-faceted approach to efficiency gains, addressing both power savings and cooling effectiveness.

The compressor shell temperature for 0.3% CuO blended nano biodegradable refrigeration oil showed a reduction of approximately 23% compared to POE68. The power consumption of 0.3% CuO blended nano biodegradable refrigeration oil was reduced by 5.02% when compared to POE68. The coefficient of performance for 0.3% CuO blended nano biodegradable refrigeration oil increased by 45% relative to POE68. (Vithya *et al.* 2020)

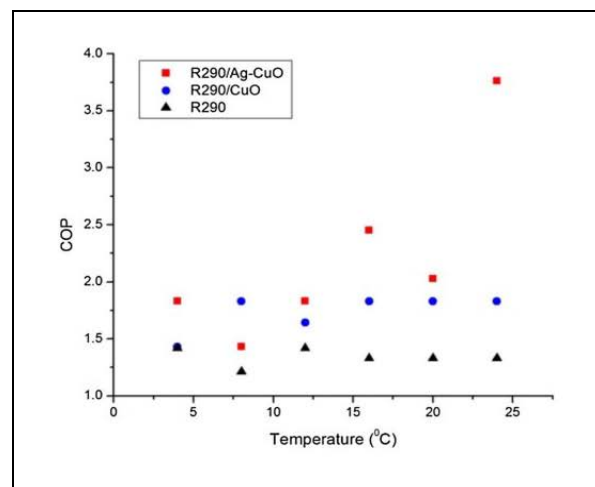


Fig. 9: Variation in COP of system with CuO and Ag doped CuO nanorefrigerant (Manikanden *et al.* 2019)

The COP of the CuO nano-refrigerant was found to be 29% higher compared to that of pure R290. When Ag-doped nano-CuO was blended with R290, the COP increased by 6% over the CuO nano-refrigerant as shown in Fig. 9. Additionally, the refrigeration effect was observed to be greater with Ag-doped CuO nano-refrigerant compared to the other refrigerants tested. The CuO nanorefrigerant reduced the refrigerator's power consumption by 15% in comparison to pure R290, while the Ag-doped CuO nanorefrigerant lowered power consumption by 28%. Thus, the experimental results demonstrated that the Ag-doped CuO nanorefrigerant outperformed pure R290, contributing to greater energy efficiency (Manikanden *et al.* 2019).

The system was tested with pure R600a and CuO nanoparticles at two concentrations (0.02857 % wt/wt and 0.05714 % wt/wt). Nanoparticles improved the performance compared to pure refrigerants, offering greater savings at higher ambient temperatures. Energy consumption was reduced by 4% and 8.24% with lower concentrations at 27°C and 38°C, respectively. CuO-R600a nanorefrigerants exhibited lower compressor

discharge temperatures compared to pure R600a. The average reduction in discharge temperature due to 0.02857 % wt/wt and 0.05714 % wt/wt nanoparticles was 3.86 % and 6.44 % at 27 °C and 38 °C, respectively (Pipewala *et al.* 2024).

These benefits suggest that CuO nanoparticles are well-suited for use in systems employing hydrocarbons, which are valued for their low environmental impact and have become increasingly popular in modern refrigeration technology. The ability of CuO nanoparticles to work effectively across various hydrocarbon refrigerants highlights their adaptability in diverse system designs and refrigerant types.

Overall, the research on CuO nanoparticles in refrigeration systems, spanning a wide array of studies, underscores their substantial potential for enhancing performance and efficiency. By delivering improvements in COP, reducing compressor energy demands, enhancing cooling performance, and optimizing lubricant stability, CuO nanoparticles offer a promising avenue for innovation in refrigeration technology. These consistent findings reveal how CuO nanoparticles can support both performance and environmental goals in refrigeration, making them a highly valuable addition for next-generation, energy-efficient, and environmentally friendly cooling solutions.

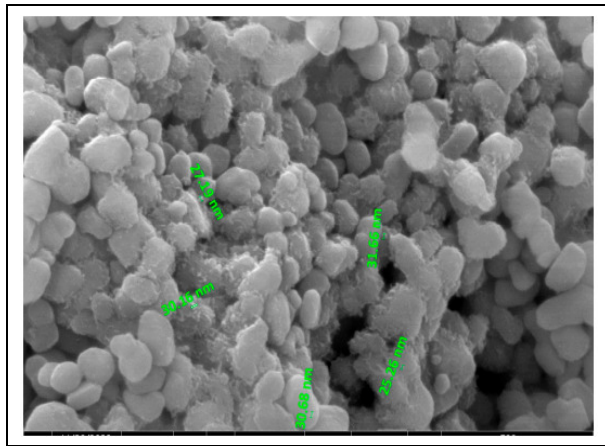


Fig. 10: SEM image of TiO₂ nanoparticle (Bibin and Gundabattini, 2023)

5. EFFECT OF TiO₂ NANOPARTICLES

Extensive research on TiO₂ nanoparticles in refrigeration systems has revealed remarkable improvements across various configurations and refrigerant types, underscoring the versatility and effectiveness of TiO₂ as an additive for enhanced performance in cooling systems. These studies have documented significant gains in energy efficiency, COP, heat transfer capabilities, and even system durability, demonstrating the potential of TiO₂ nanoparticles to advance refrigeration technology.

In systems combining R134a with mineral oil and TiO₂, energy savings reached an impressive 26.1% compared to systems using conventional POE oil, indicating that TiO₂ nanoparticles can enhance energy performance even with standard refrigerants and lubricants (Saidur *et al.* 2011). This energy reduction is particularly promising for retrofitting existing R134a systems to achieve immediate energy savings without extensive modifications.

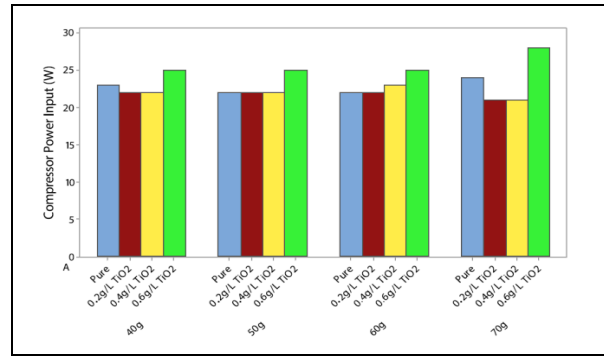


Fig. 11: Compressor power consumption variation of the varied refrigerant charges based on the pure mineral oil refrigerant and varied concentration of nano-lubricants (Adelekan *et al.* 2017)

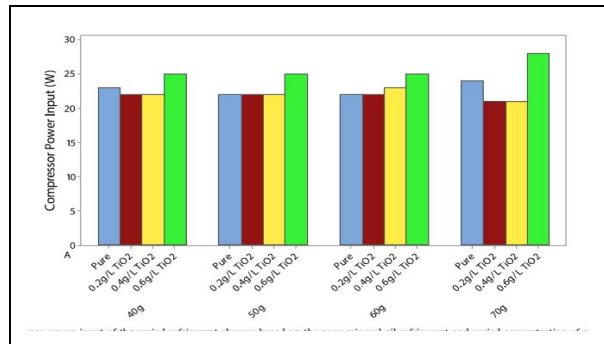


Fig. 12: Cooling capacity variation of the varied refrigerant charges (Adelekan *et al.* 2017)

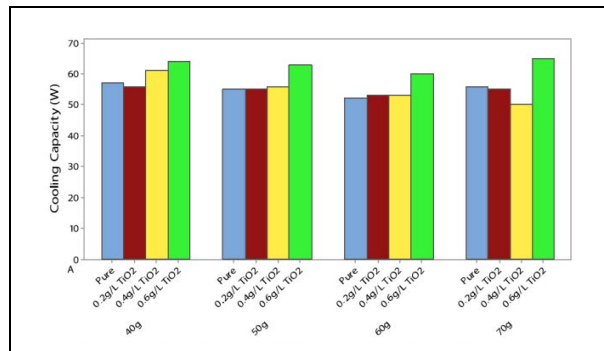


Fig. 13: Coefficient of performance variation of the varied refrigerant charges (Adelekan *et al.* 2017)

In systems utilizing R600a (Isobutene) as the refrigerant, the addition of TiO₂ nanoparticles resulted in

a 9.6% reduction in energy consumption when compared to systems using pure R600a. This finding illustrates TiO₂'s compatibility with hydrocarbon refrigerants and its ability to boost performance while maintaining the eco-friendly profile of hydrocarbons like R600a (Bi *et al.* 2011).

The study examined the impact of incorporating a low concentration of TiO₂ nanoparticles into mineral oil-based lubricants on their viscosity, lubrication properties, and the overall performance of a Vapor Compression Refrigeration System using R12 as the working fluid. The experimental results showed that a 0.01% volume fraction enhanced the average heat transfer rate by around 3.6%, reduced the average compressor work by approximately 11%, and led to a 17% improvement in the COP due to the presence of nanoparticles in the lubricating oil (Krishna *et al.* 2012).

An experimental study was conducted to examine the effects of different mass charges of Liquefied Petroleum Gas (40 g, 50 g, 60 g, and 70 g), enhanced with varying concentrations of TiO₂ nanoparticle/mineral oil (0.2 g/L, 0.4 g/L, and 0.6 g/L nano-lubricants), in a domestic refrigerator. The findings revealed a 13.7% reduction in power consumption, a 16.1% increase in cooling capacity, and a 12% improvement in COP due to the addition of nanoparticles in the system. The lowest compressor power input was 21 W, achieved with 70 g of LPG combined with either 0.2 g/L or 0.4 g/L nano-lubricants as shown in Fig. 11. The highest cooling capacity of 65 W was obtained with 70 g of LPG and a 0.6 g/L concentration of nano-lubricant as shown in Fig. 12, while the highest COP of 2.8 was achieved with a 40 g LPG charge and a 0.4 g/L concentration of nano-lubricant as shown in Fig. 13 (Adelekan *et al.* 2017).

One of the studies in TiO₂ research involved an LPG/ TiO₂-MO (mineral oil) lubricant combination, which achieved an exceptionally high COP of 56.32% and a second-law efficiency of 47.06%. The second law efficiency of the vapor compression refrigeration system can be expressed as the ratio of the actual COP of the cycle to the maximum COP of the cycle under the same conditions. Not only did this configuration improve performance metrics, but it also extended the lifespan of the compressor, underscoring TiO₂'s ability to support both efficiency and equipment durability in refrigeration systems (Gill *et al.* 2018).

Another significant finding came from research involving R600a refrigerant with TiO₂ nanoparticles, which showed a 17.39% increase in refrigeration capacity and an impressive 62.54% improvement in COP compared to similar systems using LPG refrigerants. These results suggest that TiO₂ can dramatically enhance the cooling capabilities and efficiency of hydrocarbon-based refrigerants, making it a valuable addition for those

seeking alternatives to traditional refrigerants with higher environmental impact (Gill *et al.* 2019).

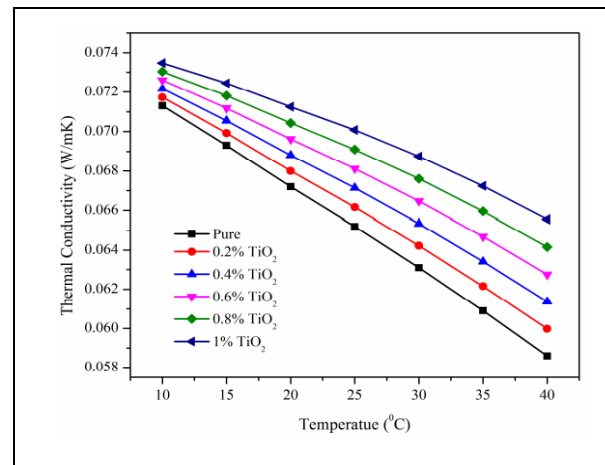


Fig.14: Variation in thermal conductivity of refrigerant blended with TiO₂ Nanoparticle with changes in temperature (Bibin and Gundabattini, 2023)

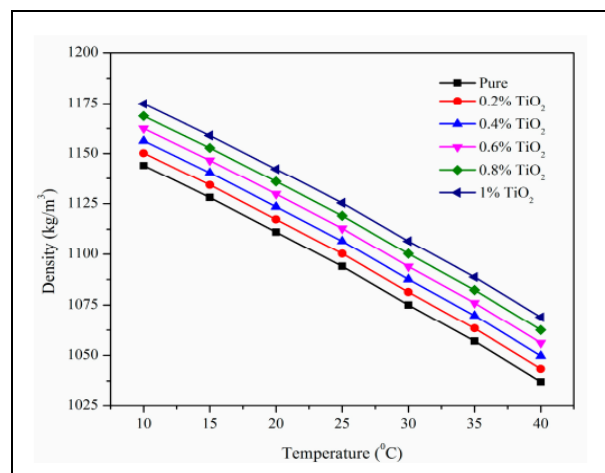


Fig. 15: Variation in density of refrigerant blended with TiO₂ nanoparticle with changes in temperature (Bibin and Gundabattini, 2023)

Research has also shown that combined LPG/R600a systems with TiO₂ nanoparticles deliver exceptional results. For example, these systems achieved COP increases of 27.6% with LPG and 14.3% with R-600a, accompanied by significant reductions in power consumption-34.6% for LPG and 35.15% for R600a (Ajuka *et al.* 2017). These improvements highlight TiO₂'s adaptability across different refrigerants and mixed refrigerant systems, suggesting that it can be tailored to optimize performance in a range of cooling applications.

In TiO₂-R134a nanorefrigerant systems, enhanced thermophysical and heat transfer properties were observed. Notably, there was a 30.20% increase in the heat transfer coefficient at a 1.5% TiO₂ concentration,

which translates to more efficient heat exchange processes within the system. This capability is particularly valuable for R134a systems, as it demonstrates TiO₂'s potential to improve not only energy efficiency but also cooling speed and overall thermal management (Sanukrishna *et al.* 2018). Furthermore, ammonia-water absorption systems with TiO₂ nanoparticles achieved a 27% increase in COP, expanding TiO₂'s application range to absorption systems that are commonly used in industrial and larger commercial refrigeration units (Jiang *et al.* 2019).

Table 3. Effect of TiO₂ nanoparticles in refrigeration system of different refrigerant

Source	Refrigerant	Observed Effect
Saidur <i>et al.</i> (2011)	R134a	26.1% energy savings compared to POE oil
Bi <i>et al.</i> (2011)	R600a	9.6% energy reduction compared to pure R600a system
Krishna <i>et al.</i> (2012)	R12	Heat transfer rate increased by about 3.6%, the compressor work reduced by about 11%, COP improvement of about 17%.
Ajuka <i>et al.</i> (2013)	LPG + TiO ₂ (0.15 wt%) / R600a + TiO ₂	COP increased by 27.6% (LPG) and 14.3% (R600a); power consumption reduced by 34.6% (LPG) and 35.15% (R600a)
Adelekan <i>et al.</i> (2017)	LPG	13.7% reduction in power consumption, 16.1% increase in cooling capacity and 12% increase in C. O. P.
Gill <i>et al.</i> (2018)	R134a	Improved thermophysical and heat transfer properties; heat transfer coefficient increased at 1.5% concentration
Gill <i>et al.</i> (2019)	LPG	Highest COP of 56.32% and second law efficiency of 47.06%, extended compressor life
Sanukrishna <i>et al.</i> (2018)	R134a	30.20% increase in the heat transfer coefficient at a 1.5% TiO ₂ concentration
Jiang <i>et al.</i> (2019)	Ammonia-water absorption	Enhanced COP
Gill <i>et al.</i> (2019)	R600a	17.39% higher refrigeration capacity, 62.54% higher COP than LPG-based system
Bibin and Gundabattini, (2023)	R1234yf	Enhanced heat transfer coefficient and pressure drop

The most recent studies have explored TiO₂'s impact in systems using the environmentally friendly R1234yf refrigerant. These TiO₂/R1234yf nanorefrigerants showed remarkable improvements in thermodynamic performance, with a 134.03% increase in the heat transfer coefficient and an 80.77% increase in pressure drop. Such improvements are crucial for

ensuring efficient, stable, and low-energy cooling in systems utilizing newer, low-global-warming refrigerants like R1234yf, making TiO₂ an attractive option for future refrigeration technologies that aim to reduce environmental impact (Bibin and Gundabattini, 2023).

Collectively, these studies spanning multiple refrigerant types, system configurations, and performance metrics demonstrate TiO₂'s potential to revolutionize refrigeration technology. The consistent benefits observed from COP increases and energy reductions to enhanced heat transfer and reduced pressure drops highlight the adaptability and efficacy of TiO₂ nanoparticles in both conventional and environmentally sustainable refrigeration systems. Through this body of research, TiO₂ has proven to be a valuable tool for improving refrigeration efficiency, extending equipment lifespan, and supporting the global transition towards greener cooling solutions.

6. CONCLUSION

In conclusion, the integration of nanoparticles such as Al₂O₃, CuO, and TiO₂ into refrigeration systems represents a significant advancement in cooling technology, with the potential to transform energy efficiency approach and performance in this critical sector. The extensive research highlights consistent improvements across various configurations and refrigerants, demonstrating the capability of these nanoparticles to enhance COP, reduce energy consumption, and improve thermophysical properties, even at remarkably low concentrations.

The benefits observed in domestic applications, commercial refrigeration, and innovative systems like diffusion absorption refrigeration underscore the versatility of nanoparticle technologies. Notably, the ability of these nanoparticles to enhance cooling capacity while minimizing operational costs positions them as essential components in the development of sustainable refrigeration solutions. The considerable energy savings and performance gains achieved with Al₂O₃, CuO, and TiO₂ not only contribute to reduced environmental impact but also align with global efforts to transition towards more sustainable energy practices.

As the demand for efficient and eco-friendly refrigeration continues to grow, the on-going exploration of nanoparticle applications will play a pivotal role in shaping the future of cooling technologies. Further research and development in this field will be crucial for optimizing formulations, ensuring compatibility with various refrigerants, and exploring new applications in advanced refrigeration systems. Ultimately, the promising results from studies on these nanoparticles pave the way for innovative solutions that can significantly enhance the efficiency and sustainability of

refrigeration systems worldwide, supporting a greener and more energy-conscious future.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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