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# Enhancing Vapour Compression Refrigeration Performance: A Comprehensive Review of Nanolubricants, Nanorefrigerants and Hybrid Nanofluids

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## ABSTRACT

The overview of nanolubricants, nanorefrigerants and hybrid nanofluids is presented in this review study along with its significance in improving the performance of vapour compression refrigeration systems. Nanolubricants, nano refrigerants and hybrid nanofluids have recently proved extraordinary potential to improve performance by dispersing nanoparticles in base fluids and lubricants. A comprehensive analysis is done to determine how hybrid nanofluids, nanorefrigerants and nanolubricants affect energy conservation. This review highlights the critical role of nanolubricants, nanorefrigerants and hybrid nanofluids in achieving superior performance, reduced energy consumption and enhanced refrigeration effects in vapour compression refrigeration systems. Application of nanoparticles in refrigerants, lubricating oil and dispersion of hybrid nanofluids in refrigeration system are discussed and summarized. The challenges and possibilities for future research are identified which will lead to innovative techniques.

**Keywords**: Nanolubricants; Nanorefrigerants; Hybrid nanofluids; Vapour compression refrigeration system; Coefficient of performance.

## 1. INTRODUCTION

Sundar *et.al* (2017) ensured significant energy savings remains one of the foremost challenges for household, commercial and industrial refrigeration systems. Employing nanoparticle suspensions in refrigerants and nanolubricants along with the use of hybrid nanofluids represents a modern approach to boost refrigerator performance. Nanorefrigerants, nanolubricants and hybrid nanofluids have been effectively integrated into vapour compression refrigeration systems (VCRS), demonstrating notable potential for enhancing performance and promoting energy conservation. Traditionally, nanoparticles have been added by dispersing them directly into the refrigerant or into the compressor's lubricating oil. However, a more recent approach involves the use of hybrid nanofluid mixtures containing two or more different types of nanoparticles which have shown promising improvements in system efficiency.

Babarinde *et al.* (2020) investigated the application of nanolubricant with graphene in R600a refrigeration system. Three samples of 0.2 g/L, 0.4 g/L and 0.6 g/L nanolubricant with graphene concentrations were dissolved in the base lubricant. The refrigerant mass concentrations of 50 g, 60 g and 70 g of refrigerant were considered for this study. The output given by R600a with nanolubricant was greater in comparison with base lubricant. The coefficient of performance (COP) enhanced up to 3.2 with graphene nanolubricant concentration of 0.2 g/L. With R600a mass charges of 50 g, 60 g and 70 g combined with a 0.2 g/L graphene nanolubricant, the system attained peak cooling capacities. The minimum consumption of power 0.0653 W was obtained with use of 60 g/R600a in 0.2 g/L lubricant containing graphene nanoparticles. This work also observed that R134a refrigeration systems involve high energy consumption and environmental concerns. In this study, the researcher focused on reducing energy consumption by using multi-walled carbon nanotubes (MWCNT) nanolubricant in an R600a refrigeration system by replacing the conventional R134a system with nanolubricant formulations at mass concentrations of 0.4 and 0.6 g/L and refrigerant charges of 50, 60 and 70 g. The incorporation of MWCNT led to enhanced COP values ranging from 2.6 to 2.8 and 2.6 to 2.9 maintaining a compressor power usage of 0.0639 kW.

Pico *et al.* (2019, 2020) investigated the involvement of diamond nanoparticles at 0.1 % and 0.5 % mass fractions and nanolubricants formed with polyol ester (POE) refrigeration oil. An experiment was conducted in R32 refrigerator as alternative for R410aA. The synthesis of diamond nanolubricants was executed to evaluate the impact of VCRS performance and

synthesis of diamond nanolubricants. In addition, linearly reciprocating sliding wear tests was conducted to assess the nanoparticles importance under starved lubricating situation. Inclusion of 0.1 % and 0.5 % nanaoparticle mass fraction reduces the friction and wear by approximately 4 % and 30 %. The experiment was conducted using R410a refrigerant focused on evaluating COP, refrigeration effect and compressor power consumption. The results showed an improvement in COP by 0.5 and refrigeration effect by 5.0 % along with a reduction in compressor discharge temperature. The addition of diamond nanolubricants further enhanced the system's performance, increasing the COP by 4 % and 8 % with nanoparticle concentrations of 0.1 % and 0.5 %, respectively. Additionally, the system with the highest mass content of diamond nanoparticles exhibited an approximate 7 % increase in refrigeration effect.

Bi *et al.* (2011) analyzed experimentally using an R600a refrigerator with $TiO_2$ nanoparticles. The performance of the refrigerator was estimated by significant variables like freezing capacity and power consumption. These methods provided insights into the system's efficiency and cooling capability under varying operational conditions. The results indicate that R600a infused with titanium oxide operated efficiently and reliably. Compared to a conventional R600a system, the refrigerator exhibited significantly improved performance. With the addition of 0.5 g of titanium oxide per litre, energy consumption was reduced by 9.6 %, and the freezing rate was notably faster than that of standard R600a. The different types of nanoparticles and methods are indicated in Fig.1.

According to Kumar *et al.* (2013), the performance of the included refrigerant to transfer heat is what determines how well a refrigeration system performs. Due to increased power consumption and the limited heat transfer capacity of the refrigerant, lubricants and nanofluids were employed to enhance heat transfer and reduce energy consumption. For improved heat transfer capabilities, aluminium oxide nanofluids were used, and the surfaces of an $Al_2O_3$ nano refrigeration system were investigated numerically. Incorporating aluminium oxide nanofluids resulted in a 11.5 % reduction in compressor power consumption and a 19.6 % enhancement in the COP of the system.

Javadi and Saidur (2013) studied the effect of nanorefrigerants on environmental elements such as energy conservation and greenhouse gas emission reduction. Varying percentages of $TiO_2$ and $Al_2O_3$ nanorefrigerants were utilized in the refrigeration system with R134a. A new environmentally friendly technology has been developed by introducing $TiO_2$ nanoparticle/mineral oil at 0.1 % that resulted in a 25 % reduction in energy usage and a drop in greenhouse gas emissions.

Anish *et al.* (2020) carried out experimental investigation of $CuO/Al_2O_3$ nanoparticle used in R22 refrigeration system. Here, the energy usage on the performance of the refrigerator was studied and the results showed improved heat transfer. At 0.05 % concentration of nanoparticles, the COP of refrigeration rose from 0.58 to 0.62, cooling capacity likewise improved, and compressor power usage decreased. Numerous studies have shown the use of nanorefrigerants and nanolubricants in different parts of vapour compression refrigeration systems. This review summarizes the importance of nanorefrigerants, nanolubricants and hybrid nanofluids to improve the performance and studies related to energy consumption.

## 2. PROSPECTS OF NANOLUBRICANTS

The review initially focuses on different categories of nanolubricants adopted in refrigerators and their overall impact on system performance. Tables 1, 2 and 4 provide a summarized overview of the findings from the review. Adelekan *et al.* (2019a) dispersed $TiO_2$ nanoparticles and studied the effect of $TiO_2$ combined with R600a as working fluid. The effectiveness of the refrigerator was evaluated by analyzing various factors, including compressor energy consumption, refrigeration effect, COP, and the pull-down test. Using R600a with nanolubricants at a charge of 40 g and 0.1 g/L concentration resulted in the biggest deviation in COP and a cooling capacity of 290.83 kJ/kg. The lowest power consumption of 58.28 kJ/kg was observed with $TiO_2$ nanolubricant. The experimental analysis of R600a refrigerant with 30 g mass concentration and various $TiO_2$ quantities of 0.2 g/L, 0.4 g/L and 0.6 g/L was used in a moderately changed R134a refrigerator. Significant aspects including average energy used power per ton of refrigeration (PPT), COP and average discharge temperature were investigated.

The discharge temperature ranged from 56 to 60 °C, the COP value ranged from 3.23 to 4.03, and the PPT value ranged from 0.79 to 1.05 for compressor energy usage. The acquirer of titanium oxide nanoparticles increases the cooling and energy saving capacity. Various LPG mass charges were tested in an R134a system using lubricants infused with titanium oxide nanoparticles. The experiment considered refrigerant quantities of 40 g, 50 g and 70 g along with lubricant concentrations of 0.2, 0.4 and 0.6 g/L of nanoparticles. The results showed that compressor power consumption was reduced to 21 W when using 0.2 or 0.4 g/L nanolubricants with a 70 g LPG charge. Using 40 g of LPG combined with 0.4 g/L of nanolubricant enhanced the COP to 2.8. The performance of a household refrigerator was analyzed by testing various graphene nanolubricant concentrations (0, 0.2, 0.4, and 0.6 g/L) in combination with R600a refrigerant mass charges varied from 40 g to 70 g. Discharge temperature, compressor energy usage, and cooling time for the 600a refrigeration system were found to fall to

41.92 %, 3.33 %, and 21.05 %, respectively, in opposition to the LPG refrigerator observed. The COP and freezing capacity were higher than those of an LPG refrigerator, reaching 62.54 % and 17.39 %, correspondingly. Temperature at discharge, cooling time, and compressor energy usage are all in the range of 33.33 %, 41.92 % and 21.05 % accordingly.

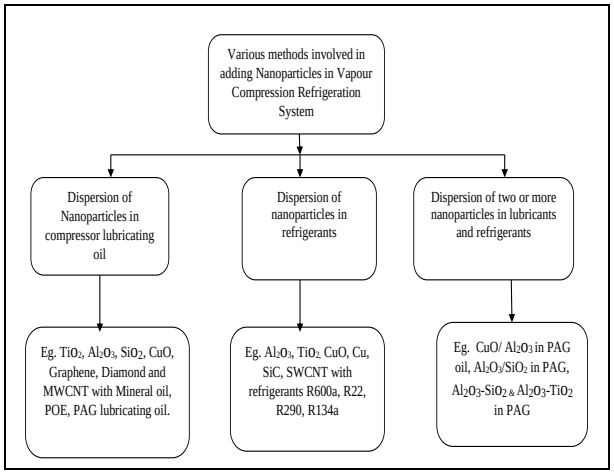



**Fig. 1: Nanoparticle dispersion methods in VCR system**

The investigation of residential refrigerator irreversibility employed LPG mass charges of 40 g, 50 g and 70 g together with different quantities of titanium oxide nanoparticles in place of R134a. All parts of the VCR system have a low rating for irreversibility. Artificial neural networks (ANN) were used to create the model.

Gill *et al.* (2018) and Sanukrishna *et al.* (2019) conducted several experiments in which nanoparticles were primarily used to enhance the tribological properties of lubricants. Additionally, studies by Jiang *et al.* (2009), Krishna *et al.* (2012) and Haque *et al.* (2016) focused on improving the thermal properties of refrigerants using nanoparticles. Research involving R134a refrigerant and $SiO_2$ nanoparticles was also carried out. The nanolubricant showed improved anti-wear performance and reduced friction based on the results. Additionally, the inclusion of $SiO_2$ at a 0.4 % concentration led to a significant increase in the heat transfer coefficient, enhancing it by up to 163.2 %.

Nanolubricants were prepared by dispersing $SiO_2$ in polyalkylene glycol (PAG) compressor oil. The nanolubricants thermal and rheological characteristics at volume fraction range value of 0.07 to 0.6 % with temperature range of 200 ℃ - 900 ℃ has been studied. The nanolubricant possesses high value of viscosity and thermal conductivity with 0.6 % volume fraction and higher than pure lubricant. The TEM image of MWCNT is illustrated in Fig. 2.

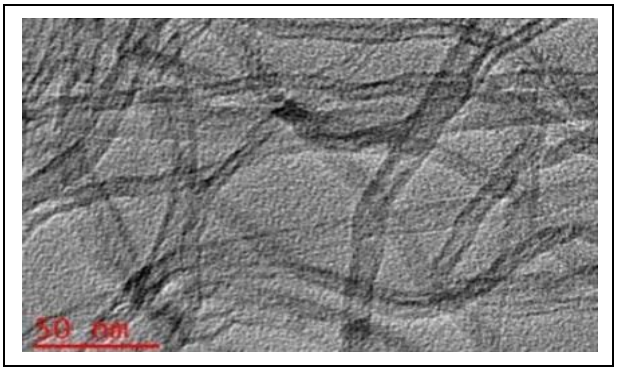



**Fig.2: TEM image of MWCNT Babarinde *et al.* (2022)**

Adopting MWCNT in R600a refrigerator consumed less energy of 13.7 % with quantity of 70 g and increase in COP of 2.9, compared to normal lubricant system (Babarinde *et al.* 2022). This research reports on effect of titanium oxide nanoparticles with PAG lubricant properties related to rheological and thermal conductivity. The nanolubricant volume concentration of 0.07 to 0.8 % and temperature at the range of 200 ℃ to 900℃ was examined. The thermal conductivity of nanolubricant raised up to 37.8 % at temperature 200 ℃ with 0.8 % volume fraction. The nanolubricants viscosity increases with improvement in volume fraction. By dispersing titanium oxide, silicon oxide, and aluminum oxide nanoparticles into PAG lubricating oil, oxide-based nanolubricants were developed. Their thermal conductivity was evaluated for volume fractions ranging from 0.07 % to 0.6 % at temperatures between 200 ℃ and -500 ℃, and their rheological properties were studied from 200 ℃ to -800 ℃. The results indicated that increasing the nanoparticle volume fraction enhanced both the thermal conductivity and viscosity of the nanolubricants. Moreover, nanolubricants containing $TiO_2$ and $SiO_2$ demonstrated superior anti-wear and friction-reduction performance compared to the pure lubricant.

Ohunakin *et al.* (2017) and Ohunakin *et al.* (2018) investigated the diffusion of titanium oxide, silicon oxide, and aluminum oxide nanoparticles in the compressor lubricating oil of an LPG refrigeration system. To enhance system performance various factors such as thermal conductivity, power consumption, viscosity at the suction and discharge ends of the compressor and cool-down time were assessed. The findings revealed that all nanolubricant-based LPG systems resulted in lower evaporator air temperatures compared to mineral oil-based LPG systems. Specifically, with $TiO_2$ and $SiO_2$ nanolubricants, the compressor consumed 13 % and 12 % less power respectively, while the LPG system alone used more power. The use of nanolubricants led to an increased COP value of 2.97.

Additionally, the efficiency of R134a refrigeration systems employing LPG refrigerant with mineral oil as a lubricant and varying concentrations of $SiO_2$ nanoparticles were examined. The thermocouple K is used to measure the suction, discharge, and condensing temperatures. Pressure gauges are used to record the appropriate pressures, and a watt meter is used to record power usage. Results indicated that LPG refrigerants enriched with nanolubricants gave -300 ℃ evaporator air temperature at lower volume charges of refrigerant compared to R134a. The COP increased to 2.05 with 0.4 g/L nanolubricant and 50 g of LPG and further reached 2.65 with 0.2 g/L $SiO_2$ and 60 g of LPG, compared to R134a refrigerants. The minimum power consumption of 28.81W was observed with the inclusion of 60 g of LPG and 0.2 g/L nanolubricant. In contrast, adding 100 g of LPG used 39.21W quantity of energy. In nanolubricants, the higher suction end thermal conductivity value of 14.51W/mK and 25.01W/mK was obtained.

Sharif *et al.* (2018) reviewed the mechanism for performance enhancement of system using refrigerants with nanoparticles and lubricants containing nanoparticles. They provided an overview of the factors that influence performance, including compressor work, COP, and tribological features. The incorporation of nanorefrigerants and nanolubricants in a system resulted in an improved heat transfer coefficients and enhanced thermal conductivity.

Narayanasarma and Kuzhiveli (2019) experimentally investigated several properties of silicon dioxide nanoparticles dispersed in POE oil and made use of nanolubricant in refrigerant compressors. The mass concentration of nanolubricant was taken as 0.01 % to 0.2 % and temperature range as 25 to 100 ℃. The increase in $SiO_2$ concentrations improved thermal and physical properties. Compressor performance was improved to 0.15 %.

Santhana Krishnan *et al.* (2018) explored the significance of nanolubricants dispersed in R134a system. Major challenges in that refrigerator were high energy consumption, and by using nanolubricants, the energy efficiency of the system was significantly enhanced. $Al_2O_3$, $SiO_2$, $ZrO_2$, and CNT were among the various nanoparticles employed in this research, along with POE lubrication. The combination of 220 mL of POE and 0.60 g of $SiO_2$ produced the greatest COP of 1.73.

Subramani *et al.* (2013) conducted experiments utilizing titanium oxide nanoparticles in R134a refrigeration system. From the results nanolubricants works usually and safely. The COP value is enhanced by 20 % and compressor power consumption was reduced by 15.4 %. Polyolester oil was combined with $Al_2O_3$ and $TiO_2$ nanoparticles of varying sizes at two different volume fractions of 0.05 and 0.1 vol. %. The performance of a system using nanolubricants was increased by 19 % with 0.05 % and 22 % with 0.1 % $Al_2O_3$ nanoparticles. $Al_2O_3$ and $TiO_2$ nanoparticles combined with POE oil reduced the compressor's power usage by 27.73 % and 14.19 %, respectively.

Haque *et al.* (2016) and Shennan *et al.* (2020), incorporated nanosheets of graphene to the base fluid that increased heat conductivity while lowering friction. For the research, three different concentrations of refrigerant oil with nanosheets comprising graphene were taken. Using refrigerant oil containing graphene nanosheet quantities of 10 mg/L, 20 mg/L, and 30 mg/L resulted in an increase in the system's freezing capacity of up to 11.1 % and a decrease in the amount of energy used over a 24-hour period of 15.4 %, 19.2 % and 20.3 %, respectively. In this study, refrigerator performance was evaluated with isobutane and graphite nanolubricants. The refrigerator was treated with nanolubricants with graphite at mass percentages of 0 %, 0.05 %, 0.1 %, 0.2 % and 0.5 %. Energy consumption decreased by 3.54 %, 4.55 %, 3.61 % and 0.64 % when utilizing graphite nanolubricant mass fractions of 0.05 %, 0.1 %, 0.2 % and 0.5 %, respectively. In addition, the pull-down times were reduced by 11.96 %, 15.22 %, 14.67 % and 10.87 % for the same corresponding nanolubricant concentrations.

Jiang *et al.* (2009) and Krishna *et al.* (2012) found that reduction in compressor work leads to enhanced coefficient of performance by specified heat removal rate method. The study explored influence of adding titanium nanoparticles in lubricating oil. Coefficient of performance of system was raised by 3.65 % including nanoparticles quantity at 0.01 % and compressor energy usage lowered to 17 %.

Lee *et al.* (2009) and Marcucci *et al.* (2020) explored combining low viscosity oil with nanoparticles. Oil and nanoparticles were used to lower the friction coefficient and improve load bearing capability. Mineral oil with a viscosity of 8 $mm^2/s$ was blended with 0.1 vol % fullerene nanoparticles. Compared to the pure oil, the nano oil exhibited a 90 % reduction in the coefficient of friction. The use of nano oil can enhance the compressor's efficiency.

Nair *et al.* (2020) investigated the use of nanoparticles in refrigeration systems utilizing vapor compression. Their study found that $Al_2O_3$ nanoparticles dispersed in PAG oil exhibited improved thermophysical characteristics compared to nanoparticles containing CuO and $TiO_2$. The use of nanoparticles enhanced the refrigerator's performance by approximately 6.5 %, and with the R134a/nano oil combination the cooling capacity reached 0.44 kW/kW while the compressor's energy consumption was 0.41 kW/kW.

**Table 1. Summary of nanolubricants**

| Refrigerant | Lubricant | Nanoparticles | Nanoparticle Mass fraction | Comments | Reference |
|---|---|---|---|---|---|
| R410a | Polyol ester | Diamond | 0.1 & 0.5 % | COP values increased by 4 % and 8 % for intensities of nanoparticles of 0.1 % and 0.5 %, respectively. 4.2 % and 7 % boost in cooling capacity. | (Marcucci *et al.* 2019) |
| R600a | Mineral Oil | Graphene | 0.2,0.4 & 0.6 g/L | Coefficient of performance improved to 3.2 with 0.2 g/L nano lubricant and minimal energy usage of 0.0653 W including 0.2 g/L | (Babarinde *et al.* 2020a) |
| R600a | Mineral Oil | $TiO_2$ | 0.2,0.4 & 0.6 g/L | In contrast to an LPG system, the COP and cooling capacity have been higher and increased to 62.54 % and 17.3 9 %, respectively. The compressor's energy usage also decreased to 33.33 % | (Jatinder *et al.* 2019) |
| R32 | POE | Diamond | 0.1 % and 0.5 % | With 0.1 % nanoparticles, the COP and cooling effect increased by 0.5 and 5.0 %, while friction decreased by 4 % | (Marcucci *et al.* 2019) |
| R134a | Polyalkylene glycol | $SiO_2$ | 0.4 % | The heat transfer coefficient elevated to 163.2 % with 0.4 % nanolubricants | (Sanukrishna *et al.* 2019) |
| LPG | Mineral oil | TiO2, $SiO_2$ and $Al_2O_3$ | 0.2 g/L | Using $TiO_2$ and $SiO_2$ compressor used 13 and 12 % less power, resulting in an improved performance of 2.97 | (Ohunakin *et al.* 2018) |
| R600a | POE | MWCNT | 0.4 g/L & 0.6 g/L | The performance has been increased from 2.6 to 2.8 and 2.6 to 2.9 by the inclusion of MWCNT at for 0.4 and 0.6 g/L. The compressor's energy usage decreased to 0.0639 kW | (Babarinde *et al.* 2020b) |
| R134a | Mineral oil | $TiO_2$ | 0.2, 0.4 & 0.6 g/L | Addition of 0.2 or 0.4 g/L nanolubricants and 70 g of LPG, lowered compressor energy usage to 21 W. Using 40 g of LPG & 0.4 g/L of $TiO_2$ the COP was increased to 2.8. | (Damola *et al.* 2016) |
| - | POE | $SiO_2$ | 0.01 % to 0.2 % | Compressor lifetime was increased to 0.15 % addition of SiO2. It also increased the viscosity, viscosity index and thermal conductivity. | (Narayanasarma and Kuzhiveli, 2019) |
| R134a | Mineral oil | $SiO_2$ | 0.2 and 0.4 g/L | Increase in performance value of 2.05 by using 0.4 g/L and 2.65 with 0.2 g/L and consumed less energy of 28.81 W by the addition of 0.2 g/L. | (Ohunakin *et al.* 2018) |
| R600a | Mineral oil | Graphene | 0,0.2,0.4 & 0.6 g/L | With R600a/70 g and 0 gram per litre, the maximum performance value of 0.76 was achieved, and compressor energy usage was reduced by roughly 65 W. | (Adelekan *et al.* 2019b) |
| R134a | POE | $Al_2O_3$ and $TiO_2$ | 0.05 & 0.1 vol. % | COP of the system was boosted by 19 % including 0.05 % and 22 % including 0.1 % Al2O3 nanoparticles | (Haque *et al.* 2016) |
| R600a | Naphthenic mineral oil | Graphite | 0.05 % & 0.1 % | Nanolubricant quantities of 0.05 %, 0.1 % ,0.2 %, and 0.5 %, 0.2 % and 0.5 % results in power usage of 3.54 %, 4.55 %, 3.61 % and 0.64 % | (Lou *et al.* 2015) |
| R12 | Mineral oil | $TiO_2$ | 0.01 % | The performance of the system was increased by 3.65 % with 0.01 % nanoparticles and 17 % reduction in compressor energy use | (Krishna *et al.* 2012) |
| R600a | SUNISO 3GS | Graphene Nanosheets | 10, 20 and 30 mg/L | There is a reduction in power usage by 15.4 %, 19.2 % and 20.3 % by the addition of graphene energy-efficient refrigerant oil. | (Bhat *et al.* 2018; Jaffri *et al.* 2018; Shennan *et al.* 2020) |

## 3. PROSPECTS OF NANOREFRIGERANTS

Sendil *et al.* (2012) experimented with aluminium oxide nanoparticles dissolved in PAG oil as a nanorefrigerant in an R134a system. Two tests on the system's energy consumption and freeze capacity were conducted. The response from the testing showed that the compressor used 10.32 % less power with 0.2 % $Al_2O_3$ and a peak COP of 3.5.

Oluseyi *et al.* (2019) observed the effects of the aluminium oxide nanoparticles employed in R134a VCR system's operating fluid. The system performance investigation included testing for energy consumption and freeze capacity. Compared to the conventional refrigerant, R134a/ $Al_2O_3$ nanorefrigerant reduced energy consumption by 0.83 to 0.97 kW. Nanorefrigerant was used to provide a cooling load that ranged from 1.72 to 2.49 kW. Because utilizing nanorefrigerants speed up cooling and required less power. To solve the challenges caused by the global energy crisis, the need for highly efficient systems became crucial. R-290 is an efficient substitute for refrigerants like R-600a that have a minimal potential to deplete the ozone layer and cause global warming. The combination of R-290 and R-600a with CuO nanoparticles significantly enhanced the thermophysical properties of the mixed nanorefrigerants.

Bhat *et al.* (2018) and Jaffri *et al.* (2018) centered on the sharply rising energy consumption, which forces conservation of energy and emissions reductions on continuous growth. R290 and R600a, which are hydrocarbon-based refrigerants, have demonstrated energy efficiency and environmental friendliness. Nanoparticles in refrigerants also enhance thermophysical characteristics and lead to improved refrigerator performance.

Mahbubul *et al.* (2013a) and Mahbubul *et al.* (2015) discussed about various nanorefrigerants. This study examined the effect of incorporating 5 volume % $Al_2O_3$ nanoparticles into an R134a on its thermophysical properties and COP. The analysis conducted under uniform mass flux in a horizontal smooth tube, using correlations, revealed that R134a system containing $Al_2O_3$ elevated exhibited enhanced thermal properties compared to the conventional system, with an improvement of 28.58 %. In heat transfer enhancement, nanorefrigerants plays an important part that is shown with an improved COP value of 15 %, thermal conductivity increases of 2.6 % and density improvement of 3.2 % when compared to the R134a refrigeration system.

Ongoing studies are focused on generating nanoparticles in concentrations ranging from 1 to 5 vol %, which are used to assess the thermal conductivity and viscosity of nanorefrigerants. The thermal conductivity increases up to 43 % with 5 vol % concentration of nanoparticle at temperature 325K. The maximum frictional pressure drop value of 301.022 kPa was obtained and compared to pure refrigerant that was 2.95 kPa. On the other side the lowest value of pressure drop was 2.48 kPa obtained for particle concentration 1 vol %. Identifying the heat transfer and pressure drop characteristics of $Al_2O_3$/R141b nanorefrigerants at varied volume fractions is the goal of this work. This study demonstrated that increasing the nanoparticle volume concentration enhanced the heat transfer properties but also led to a higher pressure drop.

**Table 2. Summary of nanorefrigerants**

| Refrigerant Used | Nanoparticle Type | Nanoparticle Mass Fraction | Summary | Reference |
|---|---|---|---|---|
| R600a | $Al_2O_3$ | 0.06 % | The use of $Al_2O_3$ nanofluids led to an 11.5 % reduction in compressor power consumption and a 19.6 % increase in the system's COP | (Bi *et al.* 2011; Kumar *et al.* 2013) |
| R600a | $TiO_2$ | 0.1 & 0.5 g/L | When 0.5 g/L $TiO_2$-R600a has been used, it used 9.6 % less energy and froze much faster than pure 600a | (Bi *et al.* 2011) |
| R134a | $Al_2O_3$ | 0.2 %V | With 0.2 % $Al_2O_3$ and a highest COP of 3.5, a decrease in compressor energy usage of 10.32 % was achieved | (Sendil *et al.* 2012) |
| R134a | $Al_2O_3$ | 0 .5g/l | In comparison to traditional refrigerant, the compressor used between 0.83 and 0.97 kW lesser energy | (Yang *et al.* 2020) |
| R134a | $Al_2O_3$ | 0 .5 % & 1 % | COP raised from 7.2 to 8.5 % by including 0.5 % aluminium oxide nanoparticles | (Kuljeet *et al.* 2014) |
| R-22 | SWCNT | 0–0.21 % | The performances, thermal conductivity, and refrigerating capacity of nanofluid refrigeration were superior than base fluid | (Vasconcelos *et al.* 2017) |
| R134a | $TiO_2$ and $Al_2O_3$ | 0.06 % & 0.1 % | 0.1 % $TiO_2$ nanoparticle/Mineral Oil resulted in energy usage of 25 %. | (Javadi and Saidur 2013) |
| R-600a & R-290 | CuO | 1 to 5 % | % By blending R-290 and R-600a with CuO nanoparticles, the thermophysical properties of the mixed nanorefrigerants were enhanced | (Jaffri *et al.* 2018) |
| R-134a | $Al_2O_3$ | 1 to 5 vol. % | The enhanced thermal conductivity value upto 43 % with 5 volume % concentration of nanoparticle at temperature 325 K | (Mahbubul *et al.* 2013a) |
| R134a, R436A & R436B | $TiO_2$ | 0.1 g/L | TiO2 nanoparticles added to the VCRS system decreased irreversibility | (Padmanabhan and Palanisamy 2012) |
| Dichlorodifluoromethane, 1,1,1,2-Tetrafluoroethane, Isobutene, R430a | $Al_2O_3$ | - | COP is significantly improved by and R436a addition of $Al_2O_3$ and significantly enhanced | (Aktas *et al.* 2015) |
| R-134a | $SiO_2$ | - | The average improvement in heat transfer was 76 % when the volume fraction of CuO nanoparticles was 0.08 % | (Henderson *et al.* 2010) |
| - | CNT | 0.15 vol. % | For concentrations of 0.45 % MWCNT, the convective heat transfer coefficient was enhanced to 0.30 vol % and 0.45 vol % or roughly 160 % | (Kumaresan *et al.* 2012) |
| R-134a | $Al_2O_3$ | 5 vol. % | $Al_2O_3$/R-134a nanorefrigerant increased density and dynamic viscosity and thermal conductivity, value up 28.58 %, 11 % and 13.68 %. | (Mahbubul *et al.* 2013b) |

Vasconcelos *et al.* (2017) experimentally tested single-walled carbon nanotubes (SWCNT) in an indirect R22-VCR system. The nanoparticle volume fractions ranging from 0 to 21 %, were investigated with mass flow rates between 40 to 80 g/s and nanofluids with input temperatures ranging from 30 °C to 40 °C. In comparison with the normal fluid, the nanofluid-based refrigeration system exhibited the thermal conductivity and refrigeration capacity of system to be superior.

Azmi *et al.* (2017) made an attempt to improve the VCR system performance by including nanoparticles to the nanolubricant and the nanorefrigerant. The impact of nanolubricants and nanorefrigerants on energy

conservation was reviewed, where the improvements in heat transfer, tribological performance and pressure drop characteristics were highlighted, showcasing the potential of these advanced fluids to enhance the efficiency of refrigeration systems.

Yee and Hermes, (2018) discussed the increase of coefficient of performance in refrigeration system. They also evaluated the refrigeration cycle irreversibility using nanofluids. The nanosuspensions not only enhanced the thermal properties, they also improved the thermal capacity compared to base solution.

Alawi *et al.* (2014), Alawi *et al.* (2015a) and Alawi *et al.* (2015b) performed detailed study of boiling and condensation process of nanorefrigerants. They also reviewed on boiling and two-phase flow process which was influenced by nanolubricants. The nanorefrigerants had higher thermal conductivity and increased the refrigeration system performance. Nanofluids have consistently outperformed pure refrigerants in terms of heat transfer performance. While much of the research has focused on the thermal conductivity of nanofluids, viscosity is equally important as it influences both pressure loss and heat conduction. Understanding and optimizing viscosity are crucial for achieving a balance between improved heat transfer and efficient flow characteristics in refrigeration systems. According to the study, as the number of nanoparticles increases, so does the viscosity of nanorefrigerants. The properties of nanorefrigerants compared to pure refrigerant, affects pressure drop and heat transfer. Unlike pure refrigerants, the nanorefrigerants affect pressure drop and heat transfer.

Padmanabhan and Palanisamy (2012) performed experiments on VCRS with nanoparticles and irreversibility process. Titanium oxide nanoparticles with 0.1 g/L dispersed in mineral oil was used as lubricating oil. The overall irreversibility value of the refrigeration system was higher than that of the POE oil refrigeration system. As a consequence, adding $TiO_2$ nanoparticles to the VCRS lowered irreversibility.

Compared to base fluids, the thermal characteristics of heat transfer fluids (referred as nanofluids) significantly improved by including ultra-fine nanoparticles. The mixes known as nanofluids, which include nanoparticles distributed in refrigerants, are unique. This review compared and clarified the effects of refrigerant containing nanoparticles on thermal and physical qualities, as well as boiling and thermophysical properties (Celen *et al.* 2014).

Aktas *et al.* (2015) explained that when pure refrigerants are combined with nanoparticles, they form a type of nanofluid known as nanorefrigerants. This research focused on five nanorefrigerants like dichlorodifluoromethane, 1,1,1,2-tetrafluoroethane, isobutene, including R430a and R436a with $Al_2O_3$ nanoparticles. It was noted that the COP significantly increased by addition of $Al_2O_3$ and highest values were obtained with R600a/$Al_2O_3$. R12 showed least amount of compression.

Kuljeet *et al.* (2014) tried to enhance the thermal and physical characteristics of currently used refrigerants by combining with nanopowder. R134a refrigerant has 20 nm-diameter $Al_2O_3$ nanoparticles disseminated in it to improve heat transfer efficiency. Following the use of nanoparticles, the COP increased from 7.2 to up to 8.5 %.

Ding *et al.* (2009) conducted an experimental study on the properties of nanoparticles related to their migration in nanorefrigerant-oil mixtures and nanorefrigerants. Additionally, performed numerical simulations to further understand the behavior and performance of these mixtures in refrigeration systems. It was observed that pool boiling nanoparticles showed better migration for both refrigerant with nanoparticle oil mixture and nanorefrigerant, which increased with mass of the refrigerant.

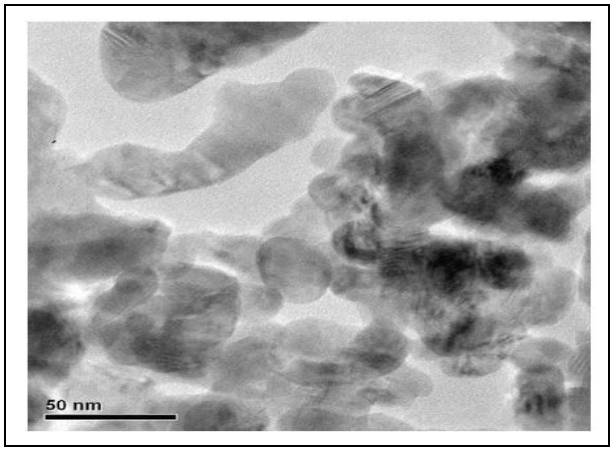



**Fig. 3: CuO nanoparticle TEM image (Peng *et al.* 2009)**

Peng *et al.* (2009) evaluated the significant effect of nanoparticle properties on drop in frictional pressure by flow boiling of nanofluid based refrigerants inside a horizontal smooth tube. Copper oxide nanoparticles with R113 as nanorefrigerant were used. The experimental results showed that by increasing nanoparticles mass fraction, the nanorefrigerants frictional pressure drop increases. The enhanced frictional pressure drop is about 20.8 %. The properties of CuO nanoparticles used in R134a refrigerator are explained in Table 3.

Ndoye *et al.* (2015) developed a model and used different types of nanoparticles like aluminium oxide, cobalt, copper oxide, iron, silicon oxide and titanium oxide in various volume fractions for simulation. It was discovered that an increment in nanoparticle concentration improved heat transfer coefficients. For

Co, CuO and Fe nanofluids, the performance evaluation criterion values went up to 80 %. The TEM image of CuO nanoparticle is shown in Fig. 3.

**Table 3. Properties of CuO nanoparticles in R113 refrigerator (Peng *et al.* 2009)**

| | Density ($kg/m^3$) | Dynamic Viscosity (Pa s) | Specific Heat (J/kgK) | Thermal Conductivity (W/Mk) |
|---|---|---|---|---|
| CuO | 6320 | - | 550.5 | 32.9 |
| R113 | 1527 | 0.0005375 | 932.5 | 0.06517 |

Kumaresan *et al.* (2012) conducted experiments using secondary refrigerants, focusing on properties that influence heat transfer by convection. These refrigerants were dispersed with CNT nanoparticles inside a tubular heat exchanger to evaluate their impact on heat transfer performance. A concentration of 0.45 vol % MWCNT enhanced the heat transfer coefficient to 160 % when mixed in mixture having water-ethylene.

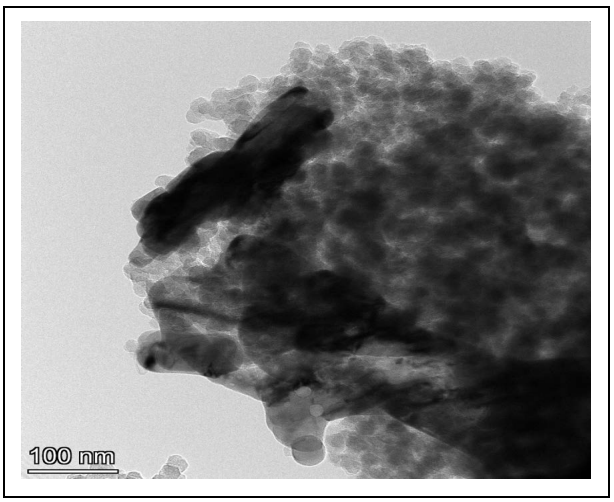



**Fig. 4: $SiO_2$/CuO hybrid nanoparticle TEM image (Vijayan and Senthilkumar, 2024)**

Henderson *et al.* (2010) studied the effect of nanoparticles on flow boiling of R134a and R134a with polyol ester mixtures. The measurements for vapor flow were of low quality (x< 20 %) and mass flux values ranged from 100 to 400 $kg/m^2s$. The diffusion of $SiO_2$ in R134a decreased the heat transfer coefficient due to difficulty in getting a stable dispersion. However, the use of CuO nanoparticles resulted in better dispersion and an increase in the heat transfer coefficient. The average heat transfer enhancement was 52 % with 0.04 % CuO volume fraction and it was 76 % with 0.08 % nanoparticle (Esfe *et al.* 2019). The rheological characteristics of MWCNT-CuO at a concentration of 30-70 % were experimentally examined using SAE50 nanofluid, at volume fractions ranging from 0 to 1 %. It was observed that when the volume fraction exceeded 0.5 %, the viscosity of the nanofluid increased.

Redhwan *et al.* (2016) studied how different nanoparticles distributed in refrigerants or lubricants might improve heat transfer, COP, and energy efficiency. The size and quantity of the nanoparticles affected the augmentation of the heat transfer coefficient. Additionally, a rise in nanorefrigerant quantity resulted in an increase in pressure and viscosity.

Hybrid nanolubricants boosted the COP by 3.5 and utilized minimum energy of 95 W compared to clean lubricant system image (Vijayan and Senthilkumar, 2024). The TEM image of $SiO_2$/Cuo nanoparticles for the preparation of hybrid nanolubricants is shown in Fig. 4.

## 4. PROSPECTS OF HYBRID NANOFLUIDS

Hamid *et al.* (2018) concentrated on improving the thermal and physical characteristics of hybrid nanofluids (table 4). The ratio of water to ethylene glycol in which the titanium oxide and silicon oxide nanoparticles are dispersed is 60:40. In the investigation, hybrid nanofluids containing $TiO_2$-$SiO_2$ at 1 % volume concentration and several combination ratios were used. When compared to base fluids, the thermal conductivity of hybrid nanofluids comprising titanium oxide and silicon oxide was raised by 16 %. Additionally, the dynamic viscosities of nanofluids were enhanced.

Nabil *et al.* (2017a) examined hybrid nanofluids and hybrid nanolubricants. Compared to typical nanofluids and nanolubricants, they have superior thermal characteristics. This analysis provides comprehensive details on the preparation procedures, ongoing developments, and heat transfer capabilities. Hybrid nanofluids play a significant role in the enhancement heat transfer. This research focused on the interactions between $TiO_2$ and $SiO_2$ nanoparticles in a water and ethylene glycol solution. The thermal conductivity of the $TiO_2$-$SiO_2$ nanofluids improved by 22 % with an increase in both temperature and nanoparticle concentration.

Hemmat Esfe *et al.* (2017) utilized an artificial neural network modeling approach to predict the thermal conductivity of hybrid nanofluids composed of SWCNTs, MgO, and ethylene glycol. Compared to single-particle nanofluids, the results obtained using hybrid nanofluids indicated that thermal conductivity improves with a 1 % increase in nanoparticle volume fraction. Additionally, a correlation was developed to enhance the understanding of thermal behavior of hybrid nanofluids, offering valuable insights for optimizing their performance in heat transfer applications.

Zawawi *et al.* (2017; 2018) experimentally examined different volume concentrations and three metal oxide composite nanolubricant blends. Thermal conductivity and dynamic viscosity were the two properties that were principally focused on in this

research. In lubricating oil, hybrid metal oxide nanoparticles such as silicon oxide and aluminium oxide, titanium oxide and silicon oxide, were dispersed. The results showed that at 303K, a volume concentration of 0.1 % $Al_2O_3$-$TiO_2$/PAG nanolubricant produced a viscosity improvement of up to 20.50 %. The hybrid aluminium oxide-silicon oxide nanoparticle concentration of 0.1 % in PAG lubricant resulted in a maximum improvement in thermal conductivity of 2.41 % at 303K. Hybrid nanolubricants were suggested for refrigerators based on the findings. To examine the properties like thermal conductivity and viscosity, $Al_2O_3$-$SiO_2$/PAG composite nanolubricants with concentrations ranging from 0.02 % to 0.1 % by volume at temperatures between 303K and 353 K were considered. Aluminum oxide and silicon dioxide nanoparticles were combined with the lubricant using a two-step process. The study found a 2.41 % improvement in thermal conductivity at 0.1 % concentration at 303 K. Additionally 9.71 % increase in viscosity was observed at 333 K with 0.1 % concentration of $Al_2O_3$-$SiO_2$ hybrid nanoparticles in PAG lubricants. These improvements suggest that the nanolubricants are suitable for use in refrigeration systems to enhance performance. The influence of adopting different nanolubricants, nanorefrigerants and hybrid nanolubricants at different concentrations and contributions for enhancing refrigerator performance, cooling effects, energy utilized by the compressor are highlighted.

**Table 4. Summary of hybrid nanofluids**

| Base fluid | Lubricant | Nanoparticle Type | Nanoparticle Mass Fraction | Summary | Reference |
|---|---|---|---|---|---|
| PAG | - | $Al_2O_3$-$SiO_2$ | 0.02 to 0.1 % | A volume concentration of less than 0.1 % of $Al_2O_3$-$SiO_2$ hybrid nanoparticles was employed in PAG lubricants. suggests using hybrid $Al_2O_3$-$SiO_2$ nano lubricants in system. | (Zawawi *et al.* 2017) |
| R22 | Polyalkylene glycol | CuO/$Al_2O_3$ | 0.05 %v | With 0.05 % nanoparticle volume fraction, higher cooling capacity, and decreased compressor power consumption, the COP of system enhanced from 0.58 to 0.62 | (Anish *et al.* 2020) |
| - | - | $TiO_2$-$SiO_2$ | 60:40 vol ratio | $TiO_2$-$SiO_2$ nanofluids improved thermal conductivity | (Hamid *et al.* 2018) |
| Ethylene glycol | - | SWCNTs /MgO | 0.05–2 % | A correlation was proposed to understand the thermal behavior of hybrid nanofluids, linking the improvement in thermal conductivity to the rise in 1 %v volume fraction | (Esfe *et al.* 2019) |
| Ethylene glycol | - | $TiO_2$-$SiO_2$ | 0.5 to 3.0 % | With an increment in temperature and volume intensity, the thermal conductivity of $TiO_2$- $SiO_2$ nanofluids elevated by 22 % | (Nabil *et al.* 2017b) |
| Polyalkylene glycol | - | $Al_2O_3$-$SiO_2$ and $Al_2O_3$-$TiO_2$ | - | The maximum increase in thermal conductivity of 2.41 % was achieved with 0.1 % hybrid $Al_2O_3$-$SiO_2$ nanoparticles. For freezers, it is recommended to use hybrid $Al_2O_3$-$SiO_2$ nanoparticles combined with PAG lubrication | (Zawawi *et al.* 2018) |

## 5. CONCLUSION

The research on nanorefrigerants, nanolubricants and hybrid nanofluids are summarized. Due to enhancement property in vapor compression refrigeration system and energy consumption reduction they could be utilized in house hold, commercial and industrial applications in future. The performance of a VCRS significantly improved by utilizing nanorefrigerants, nanolubricants and hybrid nanofluids. These advanced fluids enhance heat transfer, reduce energy consumption and improve the overall efficiency, and refrigeration effect of the system. The pull downtime of refrigerator dispersed with nanoparticles are reduced compared to normal system. This review will lead to a better solution for energy conservation issues in vapour compression refrigeration systems.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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