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Performance Analysis of R1234yf and R600a Refrigerant Mixtures with Al_2O_3 and ZnO Nano-Additive Enhanced Compressor Oils as Alternatives to R134a

Md. Gouse*, B. Omprakash

Department of Mechanical Engineering, Jawaharlal Nehru Technological University, College of Engineering, Anantapur 515002, Andhra Pradesh, India
*Corresponding author email: syedghousehyd30@gmail.com

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Abstract

The shift towards environmentally sustainable refrigerants is driven by the need to mitigate the impact of traditional refrigerants like R134a, which have high global warming potential. This study experimentally explores the performance of alternative refrigerants, R1234yf and R600a, when combined with compressor oils enhanced by Al_2O_3 and ZnO nanoparticles. A novel approach of using a hybrid nanofluid, incorporating both Al_2O_3 and ZnO nanoparticles, is proposed to optimise the performance of vapour compression refrigeration systems. The research involved preparing and characterising nano-additive compressor oils and evaluating their effects on key thermodynamic parameters across R1234yf and R600a refrigerants. The main objective of this study is to experimentally evaluate the impact of Al_2O_3 and ZnO nano-enhanced oils on refrigeration system performance, focusing on net refrigeration effect, compressor work, mass flow rate, theoretical compressor power, and coefficient of performance. The results indicate significant improvements in the coefficient of performance, mass flow rate, and net refrigeration effect with the inclusion of nanoparticles in the refrigeration lubrication system. Particularly, the coefficient of performance increased from 2.71 to 3.34 for R134a, from 2.46 to 3.26 for R1234yf, and from 2.62 to 3.12 for R600a with the optimal nanoparticle combination (0.15g Al_2O_3 + 0.05g ZnO). Similarly, compressor power and work of compression were notably reduced, demonstrating enhanced energy efficiency. The optimal mixture (COA0.15Z0.05) shows the highest coefficient of performance and reduced work of compression across all refrigerants. The study highlights that the hybrid nanoparticle approach not only boosts the performance of these refrigerants but also contributes to lower energy consumption and improved cooling efficiency.

Keywords: Global warming potential; Nanofluid; Vapour compression refrigeration system; Coefficient of performance

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1. Introduction

The growing environmental concerns surrounding climate change and the need to reduce greenhouse gas emissions have driven the global refrigeration and air-conditioning industries toward adopting more sustainable technologies [1]. Refrigerants such as R134a, which have been in widespread use, are now being phased out due to their high global warming potential (GWP) and environmental impact under international agreements like the Kigali Amendment to the Montreal Protocol [2]. R134a, with a GWP of 1,430, poses a significant threat to the environment as it contributes to the warming of the Earth's atmosphere when released. As a result, there is a compelling need to explore alternative refrigerants that not only provide similar or superior performance but also have a lower environmental footprint. In recent years, hydrofluoroolefins (HFOs) and hydro-

Nomenclature

Abbreviations and Acronyms

Al_2O_3 – aluminium oxide
COA0.05Z0.15 – compressor oil + Al_2O_3 0.05g + ZnO 0.15g
COA0.1Z0.1 – compressor oil + Al_2O_3 0.1g + ZnO 0.1g
COA0.15Z0.05 – compressor oil + Al_2O_3 0.15g + ZnO 0.05g
COA0.2 – compressor oil + Al_2O_3 0.2g
COZ0.2 – compressor oil + ZnO 0.2g
COP – coefficient of performance
FESEM – field emission electron microscope
GWP – global warming potential
HCs – hydrocarbons
HFCs – hydrofluorocarbons
HFOs – hydrofluoroolefins
ODP – ozone depletion potential
POE – polyolester (oil)
PCO – pure compressor oil
R-1234yf – 2,3,3,3-tetrafluoropropene
R134a – 1,1,1,2-tetrafluoroethane
R600a – isobutane
VCRS – vapour compression refrigeration systems
XRD – X-ray diffraction
ZnO – zinc oxide

carbons (HCs) have emerged as promising alternatives. Hydrofluoroolefins (HFOs), such as R1234yf, R1234ze(E), and R1233zd(E), are among the most prominent low-GWP alternatives to hydrofluorocarbons (HFCs). These refrigerants exhibit GWP values significantly lower than traditional HFCs, typically below 10, making them highly attractive from an environmental standpoint. HFOs also offer favourable thermodynamic properties, such as similar pressure-temperature characteristics to HFCs, which allow for easier retrofitting of existing systems with minimal modifications [3,4]. Moreover, the inherent chemical structure of HFOs results in their rapid degradation in the atmosphere, significantly reducing their potential for long-term environmental harm [5,6]. This property has led to HFOs gaining regulatory approval and widespread acceptance in various applications, including automotive air conditioning, commercial refrigeration, and stationary air conditioning systems [7]. Hydrocarbons (HCs), including R600a (isobutane), R290 (propane), and R1270 (propylene), have also garnered attention as potential refrigerants due to their excellent thermodynamic performance, natural origin, and zero ozone depletion potential (ODP) [8]. HCs exhibit favourable energy efficiency, often outperforming HFCs in terms of coefficient of performance (COP), heat transfer capacity, and power consumption. For example, studies have shown that R600a and R290 can achieve higher energy efficiency and cooling capacity compared to R134a, making them suitable for both domestic and commercial refrigeration applications [9,10]. Additionally, HCs are widely available and inexpensive, making them an economically viable alternative to synthetic refrigerants. To mitigate this issue, significant research efforts have been dedicated to improving system design, reducing refrigerant charges, and developing safety standards to ensure the safe use of hydrocarbons in various applications [11,12].

Several studies have investigated the performance of HFOs and HCs in refrigeration and air conditioning systems, highlighting their potential as viable alternatives to HFCs. Yang et al. [13] conducted a series of tests with HFO refrigerants, including R1234yf, R1234ze(E), and their blends with R134a, such as R513A and R450A, in a commercial bottle cooler. The study found no significant differences in power consumption between R134a and these new refrigerants, except for R1234ze(E), which exhibited a lower cooling capacity. Similarly, Karber et al. [14] compared the performance of R134a, R1234yf, and R1234ze(E) in household refrigerators. Their drop-in tests revealed that R1234yf had slightly higher energy consumption compared to R134a, while R1234ze(E) resulted in lower energy consumption, though its lower capacity indicated it might not be suitable for direct replacement in certain systems. Reddy et al. [15] investigated the performance of R600a in a domestic refrigeration system and found that it provided a higher COP compared to R134a while consuming less power. Similarly, Tang et al. [16] compared the energy efficiency of R290 and R134a in a heat pump system and observed a 15% improvement in energy savings with R290. These findings highlight the potential of hydrocarbons to provide environmentally friendly, energy-efficient alternatives to HFCs in refrigeration and air conditioning systems. In addition to the environmental benefits, both HFOs and HCs offer long-term cost savings due to their higher energy efficiency. Lee and Jung [17] conducted a long-term performance evaluation of R1234yf in a chest freezer and found that it provided comparable energy performance and full compatibility with the lubricant oil used in R134a systems. Suman and Kushwah [18] compared R134a, R1234yf, and R407C, noting that R1234yf had the lowest cooling capacity, emphasising the need for performance enhancements when adopting environmentally friendly refrigerants. Similarly, Yataganbaba et al. [19] performed a comparative analysis of R134a with two drop-in refrigerant mixtures composed of R134a, R1234yf, and R1234ze(E). They found that ARM-42a®, a mixture containing R1234yf and R1234ze(E), improved both COP and cooling capacity under various conditions, though it also resulted in a slight increase in power consumption.

To overcome the above limitations, recent research has focused on the incorporation of nano-additives into compressor oils to improve the performance of refrigeration systems. Nanoparticle-enhanced refrigerants have also become an area of interest in recent years. Adding nanoparticles to refrigerants has shown the potential to improve thermophysical properties, such as thermal conductivity and heat transfer, thereby enhancing the performance of refrigeration systems. Pabon et al. [20] showed that the use of ZnO nanoparticles in a refrigeration system with R1234yf resulted in significant performance improvements, including increased COP and enhanced heat transfer efficiency. Said et al. [21] explored the performance of Al_2O_3 nanoparticles in R410A refrigeration systems. Their research demonstrated a 14% increase in heat transfer efficiency and a reduction in power consumption, confirming the beneficial effects of Al_2O_3 nanoparticles. Hadi et al. [22] investigated the performance of ZnO nanoparticles in R32 refrigerants, noting significant enhancements in thermal conductivity and a 9% increase in COP.

Their results underscored the potential of ZnO nanoparticles to improve refrigeration efficiency. Senthilkumar and Praveen [23] examined the impact of CuO nano-refrigerants on the performance of R600a in a domestic refrigeration system. Their study reported a 14% increase in COP and a 9% reduction in energy consumption. This improvement was primarily attributed to the enhanced heat transfer properties of the nano-refrigerant. Bi et al. [24] performed an experimental study on TiO_2-R600a nano-refrigerants and observed an improvement in COP by 12% while maintaining similar energy consumption as pure R600a. Their study highlighted the role of TiO_2 in reducing the system's thermal resistance, thus improving overall efficiency. Madyira et al. [25] investigated the use of graphene-based nano-lubricants in R134a systems and reported a 20% reduction in compressor work and a 17% improvement in cooling capacity. Their results indicated that the addition of graphene not only enhances thermal conductivity but also reduces lubricant viscosity, which contributes to lower friction losses in the compressor. Venkatayaiah and Sthithapragna [26] reported similar findings with SiO_2-R134a nano-refrigerants, showing an 8% increase in COP and a 10% reduction in energy consumption. The study emphasised that SiO_2 nanoparticles improve the refrigerant's overall thermal conductivity, allowing for more efficient heat transfer. Vamshi et al. [27] examined various combinations of nanoparticles in refrigeration systems, finding that tailored formulations could lead to significant performance improvements. Their study highlighted the potential for developing advanced nanoparticle mixtures for optimised refrigeration. Alwi et al. [28] further investigated the use of hybrid CNT-SiO_2 nano-refrigerants in R134a systems, showing a 17% improvement in heat transfer coefficient and a 9% increase in cooling capacity. The study concluded that the hybrid nano-refrigerants offer superior performance due to the combined effects of improved thermal conductivity and enhanced dispersion stability. Javadi and Saidur [29] investigated R134a with TiO_2 and Al_2O_3, noting energy savings of up to 25% with 0.1% TiO_2 nanoparticles. Li and Lu [30] conducted a thermodynamic analysis of Al_2O_3 incorporated with various refrigerants in a VCR system. The study demonstrated that nanoparticle addition significantly enhanced heat transfer, cooling capacity, and COP, while reducing compressor work. Among all, R1233zd(E) + Al_2O_3 showed the highest performance. Katoch et al. [31] examined various nano-refrigerants like CuO-R113a and Al_2O_3-R134a but did not perform a comparative analysis under identical conditions. While numerous studies have explored the use of individual nanoparticles like Al_2O_3 or ZnO in refrigeration systems, there is a noticeable lack of research on hybrid combinations of these nanoparticles.

The novelty of this paper lies in its exploration of the combined effects of Al_2O_3 and ZnO nanoparticles as additives in compressor oils to enhance the performance of vapour compression refrigeration systems (VCRS). Unlike prior studies that typically focus on individual nanoparticles as discussed above, this research introduces a hybrid nanofluid approach by utilising both Al_2O_3 and ZnO. This hybrid combination represents a novel strategy to simultaneously optimize thermal and tribological performance in refrigeration systems. Furthermore, the paper provides a comprehensive performance evaluation of the three widely used refrigerants − R134a, R1234yf, and R600a − when used with nano-enhanced compressor oils. By assessing key thermodynamic parameters such as COP, mass flow rate, work of compression, and theoretical compressor power, this study offers new insights into how hybrid nanoparticle additives can improve overall refrigeration system efficiency. The comparative analysis across different refrigerant / nano-additive mixtures, which has not been widely explored in previous research, highlights the potential of this hybrid nanofluid for both energy-efficient and environmentally sustainable cooling solutions. Finally, the focus on alternative refrigerants such as R1234yf and R600a, alongside the incorporation of nano-additive oils, reflects the growing emphasis on sustainability in refrigeration technology, offering a lower global warming potential (GWP) while maintaining or improving system efficiency. This paper, therefore, presents a novel and practical approach to advancing refrigeration technology through nanotechnology, offering significant contributions to both energy efficiency and environmental sustainability.

2. Materials and methods

In this investigation, Al_2O_3 and ZnO nanoparticles and base lubricant (POE) were procured from the nano-research lab in India. The characterisation of both the nanoparticles by using XRD and SEM has been carried out to verify their morphology, size and purity. The dispersion of these nanoparticles was executed using the ultrasonication technique, and then the prepared samples were tested in the vapour compression refrigeration system test rig. The characterisation details and sample preparation are discussed as follows.

2.1. Characterisation of nanoparticles

The aluminium oxide (Al_2O_3) and zinc oxide (ZnO) nanoparticles used in this study were selected based on their favourable thermal and tribological properties. These nanoparticles, with average particle sizes of 40 nm for Al_2O_3 and 20 nm for ZnO, were obtained from the Nano Research Lab, located in Jharkhand, India. Detailed specifications of the Al_2O_3 and ZnO nanoparticles, including their size, purity, and other physical characteristics, are summarised in Table 1.

Table 1. Properties of Al_2O_3 and ZnO nanoparticles.

Item	Specifications	
Molecular formula	Al_2O_3	ZnO
Average particle size	40nm	20nm
Specific surface area SSA	130 m^2/g	40 m^2/g
Colour appearance	White	Milky white
Morphology	Nearly Spherical	Nearly spherical
Purity	99.9%	99.9%

The surface morphology and shape of Al_2O_3 nanoparticles, as depicted in Fig. 1a, were analysed using scanning electron microscopy (SEM). The nanoparticles exhibited a nearly spherical shape. The crystalline structure of Al_2O_3 was evaluated using X-ray diffraction (XRD) analysis within a 2Θ range of

10º–90º, as shown in Fig. 2a. Prominent diffraction peaks corresponding to aluminium oxide were identified at planes (012), (104), (110), (113), (024), (116), and (300), confirming their crystalline nature. For ZnO nanoparticles, characterisation and determination of their crystalline structure were conducted using SEM and XRD. SEM analysis, presented in Fig. 1b, revealed that the ZnO nanoparticles were also nearly spherical in shape. The crystalline structure was further verified through XRD analysis in the 2Θ range of 10–90º, as shown in Fig. 2b. Distinct diffraction peaks for ZnO were observed at 2Θ values of 31.77º (100), 34.41º (002), 36.25º (101), and 56.65º (110), confirming the crystalline characteristics of the ZnO nanoparticles.

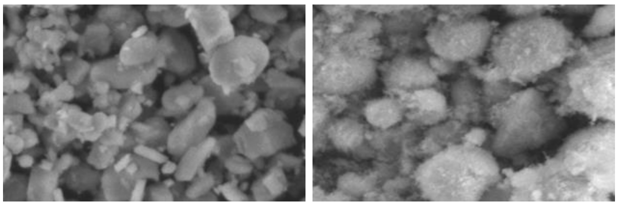
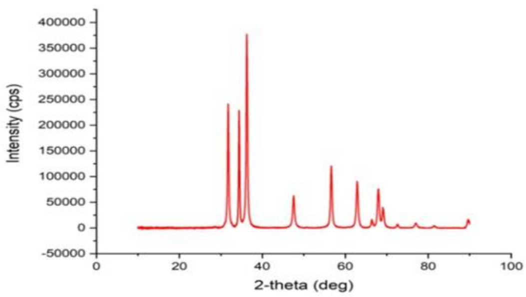
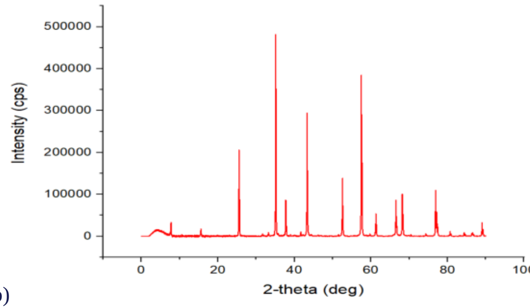

(a) (b)

Fig. 1. SEM image of (a) ZnO (b) Al_2O_3.



(a)



(b)

Fig. 2. XRD image of (a) ZnO (b) Al_2O_3.

2.2. Preparation of nano-additive compressor oil

The preparation of nano-refrigerant oil typically involves a two-step process: the first step is the synthesis of nanoparticles, and the second is their dispersion in the base lubricant. The selection of Al_2O_3 was driven by its superior thermal conductivity, which is expected to improve heat transfer within the system, while ZnO was chosen for its excellent lubricating properties and wear resistance. In this study, the combination of Al_2O_3 and ZnO nanoparticles are dispersed into the POE lubricant oil. The mixtures were prepared by carefully dispersing the nanoparticles in the base lubricant at varying concentrations. The dispersion process involved calculating the appropriate nanoparticle concentration based on mass and volume fractions, ensuring uniform dispersion in the lubricant. For this work, the mass fraction of nanoparticles is 0.2 g/L, based on findings from prior studies. For dispersing the nanoparticles, we utilised a sonication process, which ensured stable dispersion and prevented the aggregation of particles. Each mixture was stirred and ultrasonicated for an extended period to achieve uniformity, resulting in a stable nanofluid with consistent thermal and tribological properties. One important element affecting the thermal and tribological performance of nanofluids is their stability. In this investigation, stability was improved by combining mechanical churning with prolonged ultrasonication, which was followed by visual inspection. Over the course of 7 days, the produced nanofluids were inspected for sedimentation; no notable aggregation or settling was noted, suggesting good dispersion. As the compressor was hermetically sealed, the lubricating oil was continuously in contact with the refrigerants R134a, R600a, and R1234yf during operation. As a result, the nanoparticles dispersed in the lubricating oil mixed with the refrigerants, potentially enhancing the overall refrigeration effect within the vapour compression refrigeration (VCR) system shown in Fig. 3. The properties of the mixtures are provided in Table 2. The detailed nomenclature of the prepared samples is shown in Tables 3 and 4.

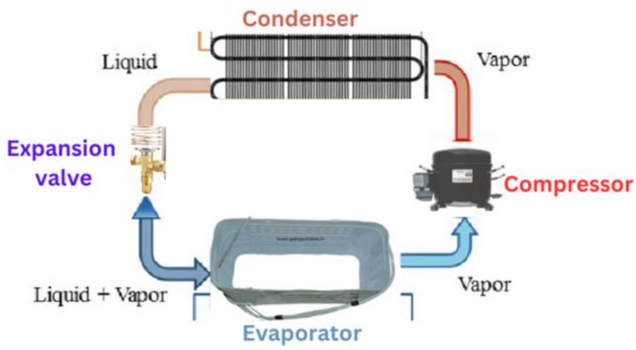


Fig. 3. Schematic appearance of VCR System.

Table 2. Properties of mixtures.

Type of mixture	Thermal conductivity, W/(m·K)	Density, g/cm³	Viscosity, mm²/s	Specific heat kJ/(kg K)
PCO	0.1232	0.946	53	1.872
COA0.2	0.1456	0.958	55	1.726
COAZ0.2	0.1332	0.976	57	1.747
COA0.1Z0.1	0.1382	0.968	56	1.767
COA0.15Z0.05	0.1407	0.965	55	1.795
COA0.05Z0.15	0.1361	0.97	56	1.811

This mixture of nanoparticles and refrigerant circulates throughout the refrigerant circuit along with the oil. Consequently, the nanoparticles also travel to the internal surfaces of the evaporator, where they contribute to an increased heat transfer rate. The volume concentration (ϕ) for each nano-lubricant mixture was calculated using the following formula:

$$\phi = \frac{m_p/\rho_p}{m_p/\rho_p + m_l/\rho_l} \times 100, \quad (1)$$

where: m_p is the mass of the nanoparticles, ρ_p is the density of the nanoparticles, m_l is the mass of the base lubricant, ρ_l is the density of the lubricant.

Table 3. Nomenclature of prepared samples.

Mixture composition	Mixture composition
PCO	Pure compressor oil
COA0.2	Compressor oil + Al_2O_3 0.2g
COAZ0.2	Compressor oil + ZnO 0.2g
COA0.1Z0.1	Compressor oil + Al_2O_3 0.1g + ZnO 0.1g
COA0.15Z0.05	Compressor oil + Al_2O_3 0.15g + ZnO 0.05g
COA0.05Z0.15	Compressor oil + Al_2O_3 0.05g + ZnO 0.15g

Table 4. A summary of the calculated mass and volume fractions is provided in the table below.

Mixture	Nanoparticles	Total mass, g	Mass fraction, g/L	Volume fraction (φ)
PCO	None	0	0	0
COA0.2	Al_2O_3	0.2	0.2	0.00072
COAZ0.2	ZnO	0.2	0.2	0.00090
COA0.1Z0.1	Al_2O_3 + ZnO	0.1+0.1	0.2	0.00081
COA0.15Z0.05	Al_2O_3 + ZnO	0.15+0.15	0.2	0.00076
COA0.05Z0.15	Al_2O_3 + ZnO	0.05+0.15	0.2	0.00086

2.3. Performance metrics calculations

The following mathematical formulations have been used to analyse the performance parameters:

1. Net refrigerating effect (NRE):

$$\text{NRE} = h_1 - h_4. \quad (2)$$

2. Mass flow rate (m_r) to obtain one TR (210 kJ/min):

$$m_r = 210/\text{NRE}. \quad (3)$$

3. Work of compression:

$$\text{work of compression} = h_2 - h_1. \quad (4)$$

4. Theoretical power of compressor (kW):

$$\text{power} = (m_r \times \text{work of compression})/60. \quad (5)$$

5. Coefficient of performance (COP):

$$\text{COP} = \text{NRE}/\text{work of compression}. \quad (6)$$

6. Heat rejection (kJ/min):

$$\text{heat rejection} = m_r \cdot (h_2 - h_3). \quad (7)$$

Enthalpy values for R134a are obtained from the standard p–h chart with respect to temperature and pressure values of the refrigerant incorporated with nanomaterials in the refrigeration system:

$$h_1 = 388 \text{ kJ/kg}, \quad h_2 = 450 \text{ kJ/kg}, \quad h_3 = h_4 = 220 \text{ kJ/kg}. \quad (8)$$

2.4. Uncertainty analysis

The uncertainty of system parameters, denoted as U_R, can be determined using the approach described by Schultz and Cole (1979). This method provides a systematic way to quantify the total uncertainty in a system, expressed mathematically as:

$$U_R = \left[\sum_{i=1}^{n} \left(\frac{\partial R}{\partial X_i} U_{Xi}\right)^2\right]^{\frac{1}{2}}. \quad (9)$$

Here, U_R represents the overall uncertainty in the parameter R, while U_{Xi} corresponds to the uncertainty associated with each independent variable X_i. The summation accounts for all n independent variables influencing the parameter R.

This equation highlights how variations in individual variables contribute to the overall uncertainty of the system. By evaluating the partial derivatives $\partial R/\partial X_i$ and combining them with their respective uncertainties, a comprehensive understanding of the system's accuracy and reliability is achieved.

To ensure clarity and reproducibility, Table 5 presents the calculated uncertainties for each parameter considered in the study. All the evaluated parameters exhibit a maximum percentage uncertainty of less than 6%. This low percentage indicates that the system operates with a high level of precision, enhancing confidence in the reliability of the reported results.

Table 5. Uncertainty of calculated parameters.

Parameters	Uncertainty
P1 (Compressor entry pressure of refrigerant)	±3 kPa
P2 (Compressor exit pressure of refrigerant)	±5 kPa
T1 (Inlet temperature of compressor)	± 0.1°C
T2 (Outlet temperature of compressor)	± 0.1°C
T3 (Outlet temperature of condenser)	± 0.1°C
T4 (Temperature at evaporator inlet)	± 0.1°C
Wc (Work of compression)	± 1.89%
COP	± 3.11

3. Results and discussion

3.1. Net refrigeration effect

Figure 4 depicts the variation in the net refrigeration effect (NRE) of various refrigerant mixtures with Al_2O_3 and ZnO nanoparticle-enhanced compressor oils. For R134a, NRE increased from 168 kJ/kg for the pure compressor oil (PCO) to 177 kJ/kg for the mixture COA0.15Z0.05, showing that the addition of nanoparticles significantly improves the refrigerant's performance. R1234yf mixtures demonstrated a similar trend, with NRE rising from 118 kJ/kg in PCO to 127 kJ/kg in COA0.15Z0.05. This is due to the fact that adding Al_2O_3 and ZnO nanoparticles increases heat absorption capacity, leading to higher refrigeration effects. In contrast, R600a consistently displayed the highest NRE values among the refrigerants, starting at 254 kJ/kg in PCO and reaching 265 kJ/kg in COA0.15Z0.05, showing superior thermal performance. The differences in NRE among the mixtures can be attributed to the enhanced thermal conductivity of the nanoparticles, which improves heat transfer rates. Among all mixtures, COA0.15Z0.05 exhibited the most significant performance improvement, likely due to the balanced combination of Al_2O_3 and ZnO. These findings highlight the effectiveness of nano-enhanced oils in improving the overall refrigeration capacity across various refrigerants. The same trend is also obtained in the study by Satapathy et al. [32].

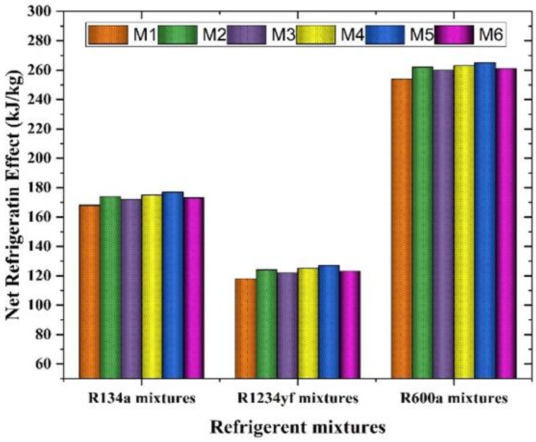


Fig. 4. Net refrigerating effect of different refrigerant mixtures.

3.2. Work of compression

Figure 5 demonstrates the work of compression across the different refrigerant mixtures. It demonstrates that the addition of Al_2O_3 and ZnO nanoparticles to compressor oil significantly reduces the energy required for compression. For R134a mixtures, the work of compression decreased from 62 kJ/kg in PCO to 53 kJ/kg in COA0.15Z0.05, indicating a substantial reduction in energy consumption. This is due to the enhanced lubrication properties provided by the nanoparticles, which reduce friction and improve the compressor's overall efficiency. A similar trend was observed for R1234yf, where the work of compression decreased from 48 kJ/kg in PCO to 39 kJ/kg in COA0.15Z0.05. The reduced compression work in these mixtures suggests that R1234yf benefits more from the nano-enhancements compared to R134a, potentially due to the refrigerant's lower viscosity and interaction with the nanoparticles. This reduced compression work can lead to overall system energy savings, making R1234yf mixtures more energy efficient when combined with nano additives. For R600a, the work of compression was higher compared to R134a and R1234yf, starting at 97 kJ/kg in PCO and dropping to 84 kJ/kg in COA0.15Z0.05. A similar trend is followed by Ajayi et al. [33]. Despite the higher initial values, the significant reduction in compression work for R600a demonstrates the effectiveness of the nanoparticles in reducing energy losses during the compression process. Overall, the mixture COA0.15Z0.05 consistently showed the lowest work of compression for all refrigerants, underscoring the positive impact of nanoparticles on system efficiency.

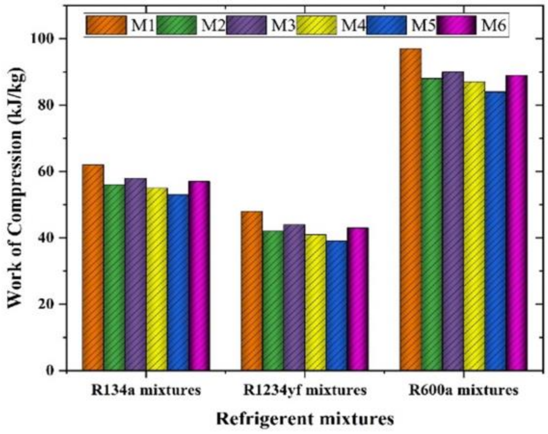


Fig. 5. Work of compression of different refrigerant mixtures.

3.3. Mass flow rate

The mass flow rate of the different refrigerant mixtures with the inclusion of Al_2O_3 and ZnO nanoparticles in the compressor oil is shown in Fig. 6.

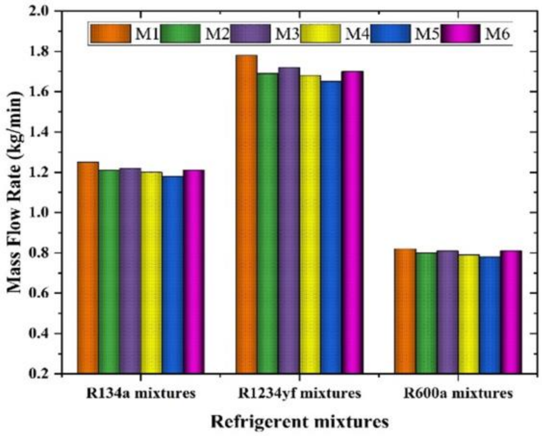


Fig. 6. Mass flow rate of different refrigerant mixtures.

For R134a, the mass flow rate decreased from 1.25 kg/min in PCO to 1.18 kg/min in COA0.15Z0.05. This reduction suggests improved efficiency in the heat transfer process, as a lower mass flow rate is required to achieve the desired cooling effect, potentially due to the enhanced thermal properties provided by the nanoparticles. R1234yf also demonstrated a reduction in mass flow rate, with values decreasing from 1.78 kg/min in PCO to 1.65 kg/min in COA0.15Z0.05, reflecting similar trends as R134a. This suggests that the addition of nanoparticles aids in reducing the refrigerant flow required, contributing to better energy efficiency in the system. Notably, R1234yf consistently exhibited the highest mass flow rates across all mixtures, which could be attributed to its lower thermodynamic properties compared to R134a and R600a. R600a showed the lowest mass flow rates overall, decreasing from 0.82 kg/min in PCO to 0.78 kg/min in COA0.15Z0.05. This further reinforces the efficiency of R600a as a refrigerant, which requires less refrigerant mass for the same cooling effect. Similar results were also discussed by Payne and O'Neal [34]. The reduction in mass flow rates across all refrigerants indicates that the nano-enhanced oils reduce friction and improve heat transfer performance, thus optimising system efficiency across the board.

3.4. Theoretical power of compression

The theoretical power of the compressor for the refrigerant mixtures with Al_2O_3 and ZnO nanoparticles introduced into the compressor oil is shown in Fig. 7.

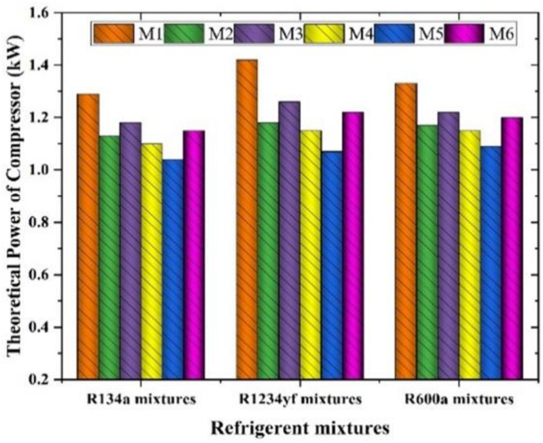


Fig. 7. Theoretical power of the compressor across different refrigerant mixtures.

For R134a, the compressor power decreased from 1.29 kW in PCO to 1.04 kW in COA0.15Z0.05. This significant reduction in power consumption indicates that the nanoparticles improve the lubrication and reduce mechanical losses within the compressor, thus enhancing overall efficiency. A similar pattern was observed with R1234yf, where the compressor power dropped from 1.42 kW in PCO to 1.07 kW in COA0.15Z0.05. The reduction in power demand highlights the positive impact of nanoparticle additives on the thermodynamic performance of R1234yf, which tends to require more power due to its slightly lower efficiency compared to R134a. The improved thermal conductivity and reduced friction achieved through the nanoparticles help mitigate this issue, leading to better energy efficiency. R600a, though displaying a lower power requirement than R1234yf, also showed improvements with the addition of nanoparticles. The theoretical power decreased from 1.33 kW in PCO to 1.09 kW in COA0.15Z0.05, reinforcing the overall trend across refrigerants. The consistent reduction in power demand across all refrigerant mixtures indicates that the Al_2O_3 and ZnO nanoparticles enhance the overall energy performance of the compressor by reducing internal resistance and improving heat transfer rates. Among all mixtures, COA0.15Z0.05 showed the most substantial reduction in compressor power, suggesting it is the optimal blend for enhancing compressor performance. This was validated by the study by Khan et al. [35].

3.5. Coefficient of performance

The coefficient of performance (COP) results for the refrigerant mixtures indicate a noticeable improvement with the inclusion of Al_2O_3 and ZnO nanoparticles in the compressor oil, as shown in Fig. 8.

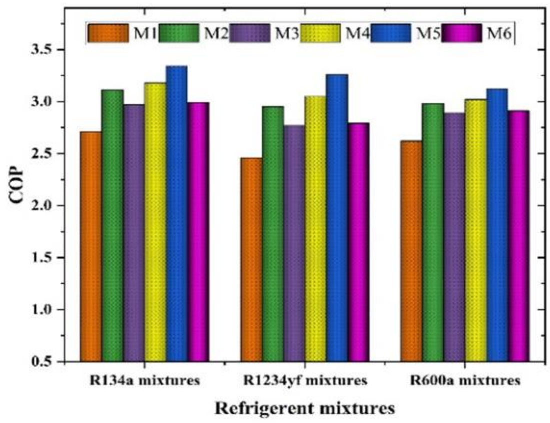


Fig. 8. COP of different refrigerant mixtures.

For R134a, the COP increased from 2.71 in PCO to 3.34 in COA0.15Z0.05, showing a significant boost in performance. This increase in COP is due to the nanoparticles enhancing the refrigerant's heat transfer efficiency, enabling the system to achieve a higher cooling effect with less energy consumption. Similarly, R1234yf demonstrated a marked improvement in COP, rising from 2.46 in PCO to 3.26 in COA0.15Z0.05. The higher COP values for R1234yf when using nanoparticle-enhanced oils highlight the potential for improving the performance of lower-GWP (Global Warming Potential) refrigerants. The increased thermal conductivity from the nanoparticles helps compensate for R1234yf's slightly lower base efficiency compared to R134a, making it a more viable alternative with enhanced energy performance. For R600a, COP also showed a consistent increase, starting at 2.62 in PCO and reaching 3.12 in COA0.15Z0.05. While R600a already exhibits high energy efficiency, the addition of nanoparticles further improved its performance, suggesting that nano-additives can optimise the refrigerant's natural thermodynamic properties. Across all refrigerants, mixture COA0.15Z0.05 (0.15g Al_2O_3 + 0.05g ZnO) exhibited the highest COP, indicating it is the most effective combination for maximising refrigeration efficiency. A similar trend was shown by Dilawar et al. [40]. The overall improvements in COP demonstrate that using Al_2O_3 and ZnO nanoparticles in compressor oil enhances system performance, resulting in better energy efficiency across various refrigerants.

4. Conclusions

The study reveals that incorporating Al_2O_3 and ZnO nanoparticles into compressor oils significantly enhances the performance and efficiency of refrigerants R134a, R1234yf and R600a. The following are the concluding remarks from the study:

- The coefficient of performance (COP) for R134a increased by 23.3%, reaching 3.34 from an initial 2.71. Similarly, R1234yf showed a 32.5% increase in COP, rising to 3.26 from 2.46, while R600a experienced a 19.1% improvement, reaching 3.12 from 2.62. This enhancement in COP reflects a notable increase in cooling efficiency.

- The compressor power decreased by 19.4% for R134a, from 1.29 kW to 1.04 kW, and by 24.6% for R1234yf, from 1.42 kW to 1.07 kW, with R600a showing an 18.0% reduction.
  - The work of compression also showed reductions, with R134a decreasing by 14.5%, R1234yf by 18.8%, and R600a by 13.4%.
  - Additionally, the mass flow rate decreased for all refrigerants, with R134a reducing by 5.6%, R1234yf by 7.3%, and R600a by 4.9%.
  - The net refrigeration effect (NRE) improved as well, with R134a increasing by 5.4%, R1234yf by 7.6%, and R600a by 4.3%.

Overall, it was observed that COA0.15Z0.05 showed the most substantial improvement in the performance of refrigerators compared with non-hybrid nano-lubricant mixtures (PCO, COA0.2, M3), suggesting it is the optimal blend for enhancing refrigerator performance. Further research can be carried out on the stability of nanoparticles in base lubricant, also with different nanoparticles like graphene oxide, CNTs, etc.. Nanoparticle-enhanced oils raise upfront costs, necessitating a cost-benefit analysis. Long-term effects on compressor materials need investigation, including wear on seals and bearings.

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