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Performance Enhancement of a Vapor Compression Refrigeration System Using Al_2O_3, CuO, and Their Hybrid Nanoparticles

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Abstract - **This study presents a comparative analysis of the performance of a vapor compression refrigeration (VCR) system enhanced with Al_2O_3, CuO, and hybrid Al_2O_3-CuO nanoparticles, each introduced at a fixed mass fraction of 1%. The objective is to evaluate the influence of different nanoparticle formulations on key performance metrics, including the coefficient of performance (COP), compressor work, and Carnot efficiency. The nanoparticles are dispersed within a secondary cooling loop and tested under steady-state operating conditions. Thermodynamic parameters are recorded for each configuration, and calculations are performed to determine the actual COP and energy input. Results show that Al_2O_3 nanoparticles enhance the COP by 22.99% and reduce compressor work by 21.65%. CuO nanoparticles achieve an even greater improvement, with a 60.73% increase in COP, thereby demonstrating superior thermal performance. Notably, the hybrid Al_2O_3-CuO nanoparticles exhibit a synergistic effect, delivering the most significant performance gains, including a reduction in compressor work of up to 30.4%. These findings highlight the potential of hybrid nanoparticles to enhance the energy efficiency and operational reliability of refrigeration systems. This work contributes to the advancement of nano-enhanced thermal systems and provides a foundation for future development of environmentally friendly, high-efficiency cooling technologies.**
Keywords: **Vapor Compression Refrigeration (VCR), Nanoparticles, Coefficient of Performance (COP), Energy Efficiency, Hybrid Nanofluids**

I. INTRODUCTION

Refrigeration systems are integral to modern life, serving critical roles in applications ranging from food preservation and air conditioning to medical storage and industrial cooling. However, with the escalating global demand for cooling and rising concerns regarding energy consumption and environmental degradation, there is an urgent need to enhance the efficiency and sustainability of these systems. Conventional vapor compression refrigeration (VCR) systems, while effective, often exhibit high power consumption, limited thermal performance under fluctuating conditions, and reliance on refrigerants that contribute to ozone depletion and global warming.

The growing demand for energy-efficient and environmentally sustainable cooling technologies has led to significant research on improving the performance of vapor compression refrigeration systems (VCRS). One promising approach is the use of nanofluids-suspensions of nanoparticles in conventional refrigerants or lubricating oils-which offer enhanced thermophysical properties such as increased thermal conductivity, improved heat transfer coefficients, and higher energy efficiency compared to traditional fluids [1], [2]. When uniformly dispersed, these nanoparticles reduce frictional losses, enhance heat transport, and improve system reliability.

Among various nanoparticles, aluminum oxide (Al_2O_3) is widely employed due to its high thermal conductivity, chemical stability, and relatively low cost. Studies have shown that incorporating Al_2O_3 nanoparticles into lubricating oils or refrigerants significantly improves the coefficient of performance (COP) and reduces compressor work [3], [4]. Similarly, copper oxide (CuO) nanoparticles, owing to their superior thermal conductivity and dispersion characteristics, have also demonstrated substantial improvements in refrigeration system performance [5]. Furthermore, hybrid nanofluids-combinations of two or more nanoparticles such as Al_2O_3 and CuO-exhibit synergistic effects that boost thermal performance and system efficiency beyond the capabilities of single-component nanofluids [6].

The integration of nanofluids into VCRS can also lead to reductions in compressor suction and discharge pressures, decreases in condenser temperatures, and improvements in heat exchange efficiency, collectively contributing to energy savings [7], [8]. However, achieving stable and homogeneous nanofluids remains a challenge, requiring methods such as ultrasonication and the use of surfactants to prevent nanoparticle agglomeration and sedimentation [9]. Overall, the application of nanotechnology in refrigeration systems presents a promising pathway for enhancing cooling performance, reducing environmental impact, and meeting evolving energy efficiency standards.

Energy efficiency has emerged as a pivotal factor in achieving sustainable development and minimizing the environmental impact of cooling systems. As energy use in air conditioning and refrigeration continues to increase, the industry is seeking innovative solutions that balance performance improvements with environmental responsibility. Among these, the use of nanofluids-engineered colloidal suspensions of nanoparticles in base fluids-has gained significant attention. Nanofluids enhance the thermal conductivity and convective heat transfer properties of conventional fluids, offering a viable approach to improving the heat exchange efficiency of refrigeration systems.

Nanoparticles such as Al_2O_3 and CuO are particularly attractive due to their thermal properties, chemical stability, cost-effectiveness, and compatibility with base fluids such as water, ethylene glycol, and polyol ester (POE) oils. Incorporating such nanoparticles into secondary cooling loops or lubricants can increase heat transfer rates, reduce temperature gradients, and lower compressor energy consumption, thereby improving overall system performance. Nevertheless, the effectiveness of nanofluids depends on factors such as nanoparticle material, size, shape, dispersion stability, and concentration. While higher concentrations can enhance thermal conductivity, they may also increase viscosity, pressure drop, and pump work, potentially leading to challenges such as clogging and sedimentation. Therefore, optimizing nanoparticle concentration is critical to achieving maximum performance without adverse side effects.

In addition to single-component nanofluids, hybrid nanofluids-combinations of two or more types of nanoparticles-are being investigated to exploit the synergistic effects of different materials. These hybrid formulations may provide superior heat transfer performance compared to single-component nanofluids due to enhanced dispersion stability and multiple thermal conduction mechanisms.

This study presents a comparative performance analysis of a vapor compression refrigeration system enhanced with Al_2O_3, CuO, and hybrid Al_2O_3-CuO nanoparticles at a fixed 1% mass fraction. The nanoparticles are dispersed in a secondary cooling loop, and the system is evaluated under steady-state conditions. Key performance indicators, including COP, compressor work, cooling capacity, and Carnot efficiency, are measured and compared against a baseline system using the pure base fluid. The objective is to determine the influence of nanoparticle type on thermal performance and to assess whether hybrid nanoparticles provide enhanced energy efficiency without compromising operational stability.

II. LITERATURE REVIEW

Recent advancements in nanotechnology have led to the exploration of nanoparticles as performance-enhancing additives in refrigeration systems. Several studies have demonstrated that incorporating nanoparticles into refrigerants or lubricants can significantly improve system efficiency. Zhelezny *et al.* [10] investigated Al_2O_3 and TiO_2 nanoparticles in refrigerant-oil nano-suspensions (RONS), reporting that the presence of nanoparticles reduced the surface tension of the base refrigerant while improving solubility. Kumar *et al.* [11] employed ZnO nanoparticles in a blended hydrocarbon refrigerant (R290/R600a) without surfactants and observed reductions in suction and discharge pressures by 17% and 21%, respectively, along with a 7.48% decrease in compressor energy consumption and a 45% increase in the coefficient of performance (COP). Similarly,

Desai *et al.,* [12] evaluated the effect of SiO_2 nanoparticles in mineral oil at various concentrations and reported COP improvements of up to 14.05%, highlighting the importance of concentration optimization. Mahbubul *et al,.* [13] found that the addition of 5 vol.% Al_2O_3 nanoparticles enhanced thermal conductivity by up to 28.58% and increased COP by 15%, although higher viscosity and density were also observed, which require careful management.

Singh [14] reviewed the broader implications of nanofluids in thermal systems, emphasizing their potential in applications such as micro-electromechanical systems (MEMS), electronics cooling, and aerospace, due to their superior thermal conductivity. Tiwari *et al.* [15] demonstrated that Al_2O_3 nanoparticles with R600a and mineral oil improved heat transfer, increased freezing capacity, and reduced power consumption by 11.5%, supporting the feasibility of nano-lubricants in domestic refrigeration. Finally, Abbas *et al.,* [16] reported that carbon nanotubes (CNTs) in polyol ester (POE) oil with R134a refrigerant enhanced COP and reduced energy consumption, with the best performance achieved at a 0.1 wt.% CNT concentration.

Collectively, these studies underscore the potential of nanoparticle-enhanced fluids to significantly improve the thermal and energy performance of refrigeration systems, though careful consideration must be given to nanoparticle type, size, concentration, and dispersion stability.

A. Experimental Setup and Working

The experimental apparatus is based on a conventional vapor compression refrigeration system (VCRS), modified to evaluate the performance of nano-enhanced refrigerants. The system consists of four primary components: a hermetically sealed reciprocating compressor, an air-cooled condenser, a capillary tube serving as the expansion device, and an evaporator. These components are interconnected with insulated copper tubing to minimize thermal losses.

The refrigeration cycle begins as the compressor compresses the refrigerant, thereby increasing its pressure and temperature. The high-pressure vapor enters the condenser, where it rejects heat to the surroundings and condenses into a high-pressure liquid. This liquid refrigerant then flows through the capillary tube, causing a sharp drop in pressure and temperature. The resulting low-pressure, low-temperature refrigerant enters the evaporator, where it absorbs heat from the cooling medium (e.g., water or air), thereby producing the desired cooling effect. The refrigerant then returns to the compressor, completing the cycle.

For this study, the base refrigerant was enhanced with nanoparticles to form nano-refrigerants. Al_2O_3, CuO, and a hybrid mixture of Al_2O_3 + CuO nanoparticles were individually dispersed into the refrigerant at a fixed 1% mass fraction. The dispersion process was carried out using ultrasonication to ensure uniform distribution and long-term stability of the nanoparticles within the fluid. Prior to charging the nano-refrigerants into the system, a vacuum pump was used to evacuate the entire circuit to remove moisture and non-condensable gases. The refrigerants were then charged using a calibrated manifold gauge set, following standard refrigeration practices to ensure consistency across all test runs.

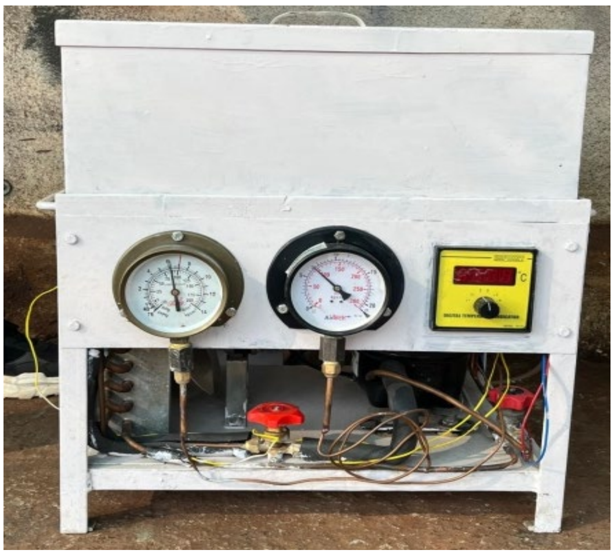

Fig. 1 Experimental set up

The experimental setup is based on a standard vapor compression refrigeration system (VCRS), modified to incorporate nano-enhanced refrigerants. The system consists of four main components: a compressor, condenser, expansion device, and evaporator, all interconnected by insulated copper tubing. A hermetically sealed reciprocating compressor compresses the refrigerant, increasing its pressure and temperature before it enters the condenser.

In the condenser, the high-pressure vapor releases heat to the surroundings and condenses into a high-pressure liquid. This liquid refrigerant then passes through a capillary tube, which serves as the expansion device, where its pressure and temperature decrease significantly. The resulting low-pressure, low-temperature refrigerant enters the evaporator, where it absorbs heat from the surrounding medium (e.g., a water tank or air chamber), thereby producing the cooling effect. The refrigerant then returns to the compressor, completing the cycle.

For this study, nano-refrigerants were prepared by dispersing Al_2O_3, CuO, and hybrid Al_2O_3 + CuO nanoparticles into the base refrigerant using ultrasonication to ensure uniform dispersion and stability. A fixed 1% mass fraction of each nanoparticle type was tested separately. The nano-refrigerants were charged into the system using a standard manifold gauge set, following proper evacuation of the circuit to eliminate non-condensable gases and moisture.

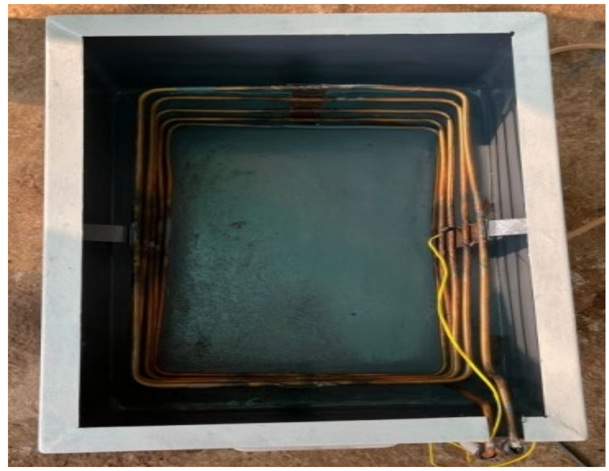

Fig. 2 Modify evaporator

The preparation of the nanofluid for this study involved dispersing Al_2O_3 nanoparticles into polyester (POE) oil to enhance the thermal performance of a vapor compression refrigeration system. Nanofluids were prepared at varying mass fractions of Al_2O_3, specifically 0.25%, 0.50%, 0.75%, and 1.00%, as well as a hybrid mixture containing 1% CuO with 1% Al_2O_3. The required nanoparticle mass corresponding to each fraction was calculated based on a 450 ml volume of POE oil, resulting in 1 g, 2 g, 3 g, and 4 g of Al_2O_3, respectively. Preparation began with mechanical stirring of the nanoparticles in the base oil for 15-20 minutes to initiate mixing, followed by ultrasonication using a probe-type ultrasonic agitator for approximately two hours. This ensured uniform dispersion, minimized agglomeration, and produced a stable and homogeneous nanofluid.

The prepared nanofluids were then tested in a refrigeration laboratory at the Scientific Indian Workshop, Miraj. Prior to charging, the vapor compression system was completely discharged by removing the existing refrigerant and oil. The system was evacuated using a service compressor to eliminate air and moisture, thereby creating the required vacuum environment for refrigerant charging. The nanofluid was introduced into the compressor through the charging valve using a funnel setup.

Once the oil was charged, the refrigerant was introduced into the system under technical supervision. Leak testing was performed using a soap solution applied to joints and connections; bubble formation indicated leakage, while no visible change confirmed a sealed system. Following a successful leak test, the air-conditioning system was operated for 15 minutes to achieve steady-state conditions. Thereafter, system performance data were recorded. Parameters such as evaporator and condenser pressures, compressor power consumption (measured via energy meter blink count), inlet and outlet temperatures of the condenser and evaporator, and dry- and wet-bulb temperatures at the inlet and outlet were measured.

This procedure was repeated consistently for each nanofluid concentration, including the hybrid nanofluid, to ensure uniform testing conditions and accurately assess the effect of nanoparticle addition on refrigeration system performance.

B. Calculation and Result

Comparative study of Al_2O_3 + CuO Nanoparticles having 1% mass fraction on Refrigeration system.

TABLE I (A) CuO READINGS FOR 1% MASS FRACTION OF NANOPARTICLES

Sl. No	Parameters	Observation	
1	Evaporator pressure	43Psi	2.96 bar
2	Condenser Pressure	170Psi	11.72 bar
3	Compressor energy meter reading for 10 blinks	11.56 sec	

TABLE I (B) CuO READINGS FOR 1% MASS FRACTION OF NANOPARTICLES

Sl. No.	Description	Symbol	Unit	Reading
1	Condenser inlet temperature	Tci	°C	62
2	Condenser outlet temperature	Tco	°C	40
3	Evaporator inlet temperature	Tei	°C	5
4	Evaporator outlet temperature	Teo	°C	8

C. Calculations

Evaporator Pressure (Pe) = 43 psi

$Pe = \frac{43}{14.5} = 2.965$ bar

Condenser Pressure (Pc) = 170 psi

$Pc = \frac{170}{14.5} = 11.724$ bar

Rotameter Flowrate = 29 LPH= $\frac{31\times10^{-3}}{3600}$ = 8.6111×10-6 m3/sec

$(COP)th = \frac{h1-h4}{h2-h1}$

$= \frac{410-258}{447-410}$ (from P-H Chart)

$= 4.27$

Compressor work $= \frac{Tc\times EMC}{10\times3600}$

$= \frac{11.56\times3200}{10\times3600}$

=1.027KW

Heat absorbed in evaporator = MeCp▲h

$= 8.6111\times10\text{-}6\times 1186.7 \times (410 - 258)$

=1.553 KJ/Sec

Where,

Me: mass of flow rate in evaporator (m3/sec)

Cp: Specific Heat of R134a

▲h: Refrigerating effect

$(COP)Actual = \frac{\text{Heat absorbed in evaporator from water}}{\text{Compressor work}}$

$= \frac{1.553}{1.027}$

=1.512

$(COP)carnot = \frac{TL}{TH-TL}$

$$= \frac{(0+273)}{(45+273)-(0+273)}$$

= 6.06 (From refrigeration Table)

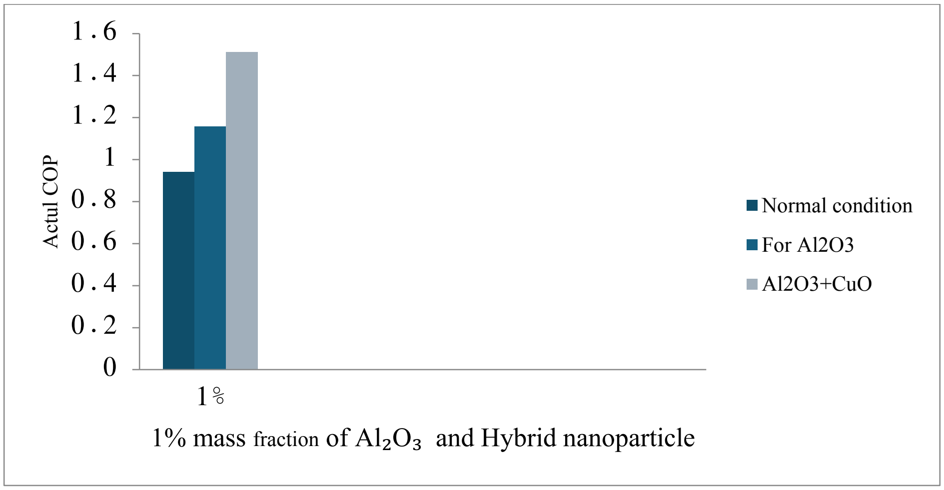

Fig. 3 Graph of 1% mass fraction of Al_2O_3 and Hybrid nanoparticle

From the above graph, it can be concluded that the addition of 1% Al_2O_3 nanoparticles increases the actual coefficient of performance (COP) of the refrigeration system by 22.99%, whereas the addition of 1% CuO nanoparticles increases the actual COP by 60.73%. Therefore, the hybrid nanoparticle formulation is more efficient than Al_2O_3 alone.

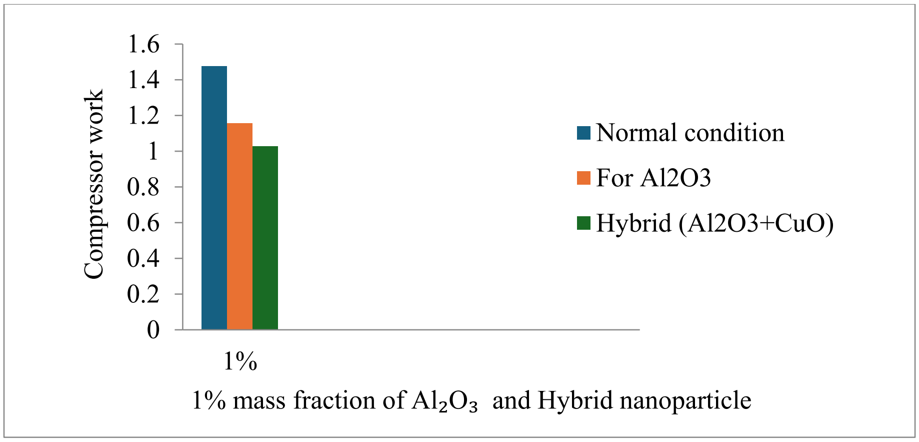

Fig. 4 1% mass fraction of Al_2O_3 and Hybrid nanoparticle

From above graph we conclude that, by addition 1% of Al_2O_3 nanoparticles Actual COP of refrigeration system is decreased by 21.65 % whereas by addition of 1% of CuO+Al_2O_3 nanoparticles in compressor work is decreased by 30.4%. Therefore, hybrid nanoparticle is more efficient the Al_2O_3.

D. Graph of Carnot COP

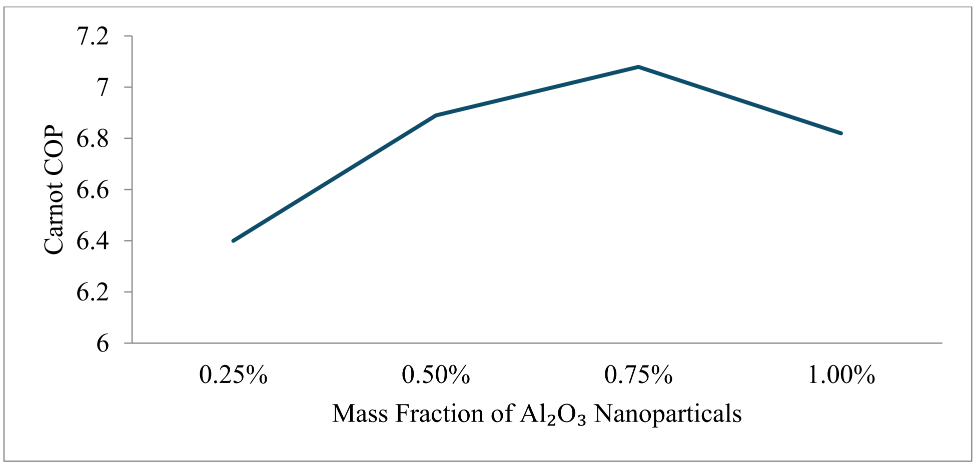

Fig. 5 Carnot Cop V/S Mass Fraction

The graph illustrates the variation of the Carnot coefficient of performance (COP) of the refrigeration system with different mass fractions of Al_2O_3 nanoparticles added to the lubricant. The baseline COP under normal conditions, without nanoparticles, is 6.56. At a 0.25% mass fraction of Al_2O_3, the COP decreases slightly to 6.40, indicating a marginal decline in performance, possibly due to initial agglomeration or increased viscosity. At a 0.50% mass fraction, a notable improvement is observed as the COP increases to 6.89, and it further rises to a peak value of 7.079 at a 0.75% mass fraction. This demonstrates that thermal conductivity and heat transfer are significantly enhanced at this concentration.

Beyond this optimum point, at a 1.00% mass fraction, the COP decreases slightly to 6.82. This reduction may be attributed to excessive nanoparticle loading, which can increase fluid viscosity and reduce heat transfer efficiency due to poor dispersion or sedimentation. Overall, the results indicate that a 0.75% mass fraction of Al_2O_3 nanoparticles provides the maximum enhancement in Carnot COP, optimizing thermal performance without compromising fluid stability or flow characteristics.

As shown in the graph, it can be concluded that as the mass fraction of Al_2O_3 increases, the compressor work of the refrigeration system decreases. The graph illustrates the variation of the Carnot coefficient of performance (COP) of the refrigeration system with different mass fractions of Al_2O_3 nanoparticles added to the lubricant. The baseline COP under normal conditions, without nanoparticles, is 6.56. At a 0.25% mass fraction of Al_2O_3, the COP decreases slightly to 6.40, indicating a marginal decline in performance, possibly due to initial agglomeration or increased viscosity. At a 0.50% mass fraction, a notable improvement is observed as the COP increases to 6.89, and it further rises to a peak value of 7.079 at a 0.75% mass fraction, showing that thermal conductivity and heat transfer are significantly enhanced at this concentration. Beyond this optimum point, at a 1.00%

mass fraction, the COP decreases slightly to 6.82. This reduction may be attributed to excessive nanoparticle loading, which can increase fluid viscosity and reduce heat transfer efficiency due to poor dispersion or sedimentation. Overall, the results indicate that a 0.75% mass fraction of Al_2O_3 nanoparticles provides the best enhancement in Carnot COP, optimizing thermal performance without compromising fluid stability or flow characteristics.

E. Graph of Compressor Work

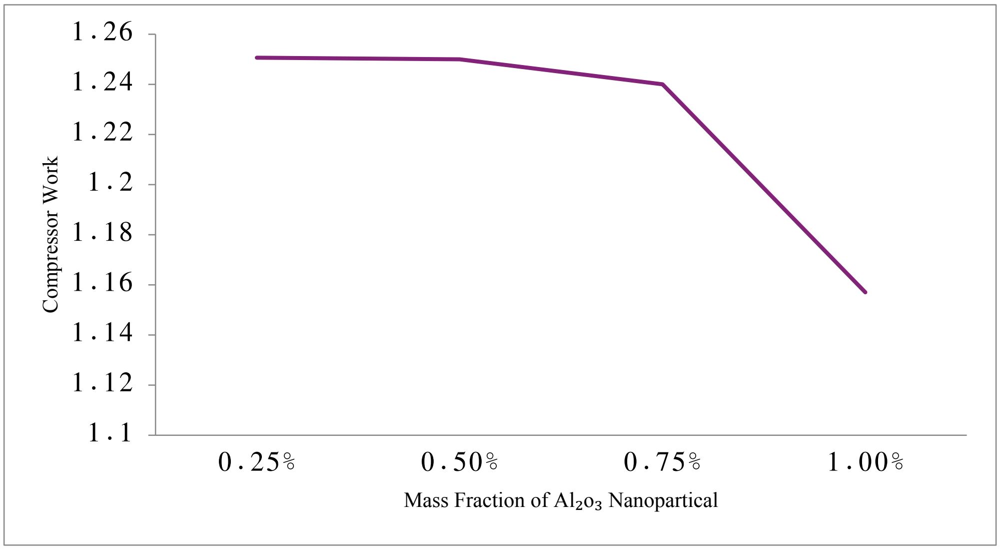

Fig. 6 Compressor Work v/s Mass Fraction

III. CONCLUSION

This experimental study evaluates the effectiveness of nano-enhanced coolants in improving the thermal performance of a vapor compression refrigeration system. Three types of nanoparticles-aluminium oxide (Al_2O_3), copper oxide (CuO), and a hybrid mixture of Al_2O_3 and CuO-were tested at a 1% mass fraction to assess their influence on key performance parameters, including the coefficient of performance (COP), compressor work, and Carnot efficiency. The results indicate that the addition of nanoparticles significantly enhances the system COP.

Among the tested nanofluids, CuO demonstrated the highest performance improvement, with a 60.73% increase in COP, attributed to its high thermal conductivity and efficient heat transfer properties. Al_2O_3 also showed a considerable improvement of 22.99%, confirming its effectiveness as a thermal performance enhancer.In addition to COP enhancement, a notable reduction in compressor work was observed, directly translating to energy savings.

Al_2O_3 reduced compressor work by 21.65%, while the hybrid Al_2O_3 + CuO nanofluid achieved the greatest reduction of 30.4%. This demonstrates the synergistic effect of combining different nanoparticles, leading to superior thermophysical properties and more efficient thermal exchange. The hybrid nanofluid outperformed the individual nanoparticle solutions, delivering both higher COP and lower compressor energy requirements, thereby offering a promising solution for improving refrigeration efficiency.

While the theoretical Carnot COP remained relatively stable, a slight peak was observed at a 0.75% Al_2O_3 concentration, suggesting an optimal concentration level beyond which performance improvements may diminish.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Use of Artificial Intelligence (AI) - Assisted Technology for Manuscript Preparation

The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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