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Enhancing the Performance of Vapour Compression Using Nanoparticles

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Abstract:- Enhancing the performance of vapor compression refrigeration systems is critical for achieving better energy efficiency and environmental sustainability. This study focuses on utilizing nanoparticles as performance-enhancing additives in refrigerants used in vapor compression cycles. Nanoparticles exhibit superior thermal properties, including high thermal conductivity and enhanced heat transfer capabilities, which can significantly boost the efficiency of both refrigerants and lubricants. Various nanoparticles such as aluminium oxide (Al_2O_3), copper oxide (CuO), and titanium dioxide (TiO_2) are evaluated for their effectiveness when dispersed in conventional refrigerants. To ensure reliable operation, proper stabilization techniques are employed to mitigate issues like particle agglomeration and sedimentation. The experimental findings reveal that incorporating nanoparticles improves the coefficient of performance (COP) by enhancing heat transfer rates and refrigeration efficiency. Additionally, the system experiences reduced energy consumption, contributing to more sustainable and cost-effective cooling solutions. The influence of nanoparticle concentration, type, and size on parameters such as thermal conductivity, pressure drop, and compressor workload is thoroughly analysed. Furthermore, the study highlights challenges related to dispersion stability and mechanical wear while discussing potential mitigation strategies. The research concludes that nanofluids, when adequately formulated, represent a promising innovation for advancing vapor compression systems. Their application can lead to improved heat transfer performance and energy savings, supporting the growing need for eco-friendly cooling technologies. Future studies should explore optimal nanoparticle formulations, investigate advanced nanomaterials, and examine compatibility with environmentally benign refrigerants to further enhance performance and sustainability. This work contributes to the ongoing efforts to develop energy-efficient refrigeration and air conditioning systems, aligning with global energy conservation and climate change mitigation goals.

I. INTRODUCTION

Over the past two decades, the use of nanomaterials in various base fluids has significantly improved heat transfer rates, leading to greater thermal system efficiency. In 1996–97, Choi S. pioneered a technique to enhance nanofluid thermal conductivity by incorporating nanoparticles [1]. This work demonstrated how metal oxide nanoparticles could improve fluid thermal conductivity [2]. Since then, extensive research has confirmed the benefits of nanoparticle-based nanofluids in enhancing thermal applications. Choi's findings facilitated the use of nanofluids in a range of thermal systems. Numerous studies on Al2O3-based nanofluids in refrigeration systems have evaluated performance factors, primarily focusing on energy consumption and the coefficient of performance (C.O.P.). Biet al. [3] investigated Al2O3 and TiO2 nanoparticles with HFC134a refrigerant in a household refrigerator, reporting a 26.1% reduction in energy consumption and other performance improvements. Jwo et al. [4] noted a 2.4% reduction in energy use and a 4.4% increase in C.O.P. when using an Al2O3–POE nano lubricant with R134a refrigerant. Sendilet al. [5] conducted experiments with Al2O3-based POE nanofluids and varied R134a charges, achieving a 10.32% energy consumption reduction and a significant C.O.P. increase. They also observed that Al2O3–POE-based nano lubricants with R134a reduced energy consumption by 2.4% and enhanced C.O.P. by 4.4%. Soliman et al. [6] combined R134a refrigerant with Al2O3–POE nanofluid to optimize the vapor compression cycle, leading to a 50% increase in the heat transfer coefficient, a 10.5% performance boost, and a 13.5% drop in energy consumption. Yusof et al. [7] also reported that incorporating Al2O3-based POE nanofluids with R134a improved system C.O.P. and reduced energy consumption by 2.1%.. The techniques of superheating and subcooling, when combined with Al_2O_3 nanofluid, have demonstrated enhanced efficiency in refrigeration systems (8). Significant improvements in heat transfer performance have been observed in vapor compression and absorption refrigeration systems using water-based Al_2O_3 nanofluid with ammonia (9). Comparative studies in the literature (13–18) reveal that other nanoparticles, such as copper oxide, carbon nanotubes, and titanium dioxide, offer superior performance compared to Al_2O_3. However, Al_2O_3-based nanofluids still show better performance than conventional refrigerants. This study focuses on the experimental performance analysis of a vapor compression refrigeration system using R134a and R600a, addressing the scarcity of data on Al_2O_3 with R600a (14). It compares the performance of Al_2O_3 nanofluid under identical conditions for both refrigerants. The concept of nanofluids, introduced by Choi, involves dispersing 100 nm nanoparticles in base fluids such as water, oil, and ethylene glycol (11). Nanofluids are increasingly applied in renewable energy systems due to their superior thermal properties and stability. Research consistently shows that nanofluids outperform traditional base fluids in convective heat transfer capabilities. [12] Efficient heat management systems are essential for the proper functioning of car radiators. A study by Choi [13] introduced nanofluids as an advanced coolant for car radiators. These nanofluids have demonstrated promising results in the renewable energy sec-

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tor, particularly in enhancing convective heat transfer properties and improving thermal conductivity. Due to these remarkable features, nanofluids have inspired further exploration into the concept of nano-refrigerants. The two main applications for nanofluids are coolants and lubricants. In refrigerant systems, nanoparticles are directly added to the refrigerant, whereas in lubrication systems, they are mixed with the lubricant before being introduced to the refrigerant [14]. Although nano lubricants (such as polyol ester oil, POE) and nano refrigerants (refrigerants containing well-dispersed nanoparticles) are distinct, many studies have focused on the thermal properties of refrigeration systems using nanofluids without distinguishing between them. As a result, the specific impact of nanoparticles on refrigeration performance has not been fully explored. However, after reviewing existing literature, we identified four key findings from previous research [15–26]. Several researchers have examined refrigeration systems that aim to reduce Global Warming Potential (GWP) and Ozone Depletion Potential (ODP), primarily through two strategies. The first involves replacing conventional refrigerants with low-GWP refrigerants, often utilizing nanofluids in the process [27–30]. While nano refrigerants contain well-dispersed nanoparticles, nano lubricants, such as POE oils, contain nanoparticles mixed with lubricants. Though they differ, studies on nanofluids' thermal properties in refrigeration systems have typically not separated them into nano refrigerants and nano lubricants. Consequently, the effect of nanoparticles on refrigeration system efficiency has not been fully assessed.

II. VCR SYSTEM

The cycle, incorporating the two mentioned modifications, is called the vapor compression cycle. This cycle is primarily used in commercial refrigeration systems due to its high efficiency and performance. A full vapor compression cycle is depicted on the T-S diagram in Fig. 3.4 and the p-v diagram in Fig. 3.5. In Fig. 3.4, a comparison is made between the vapor compression cycle (1-2-3-4) and the reversed Carnot cycle (1-2-3-4), both operating between the same temperature limits, Tk and To. In the vapor compression cycle:

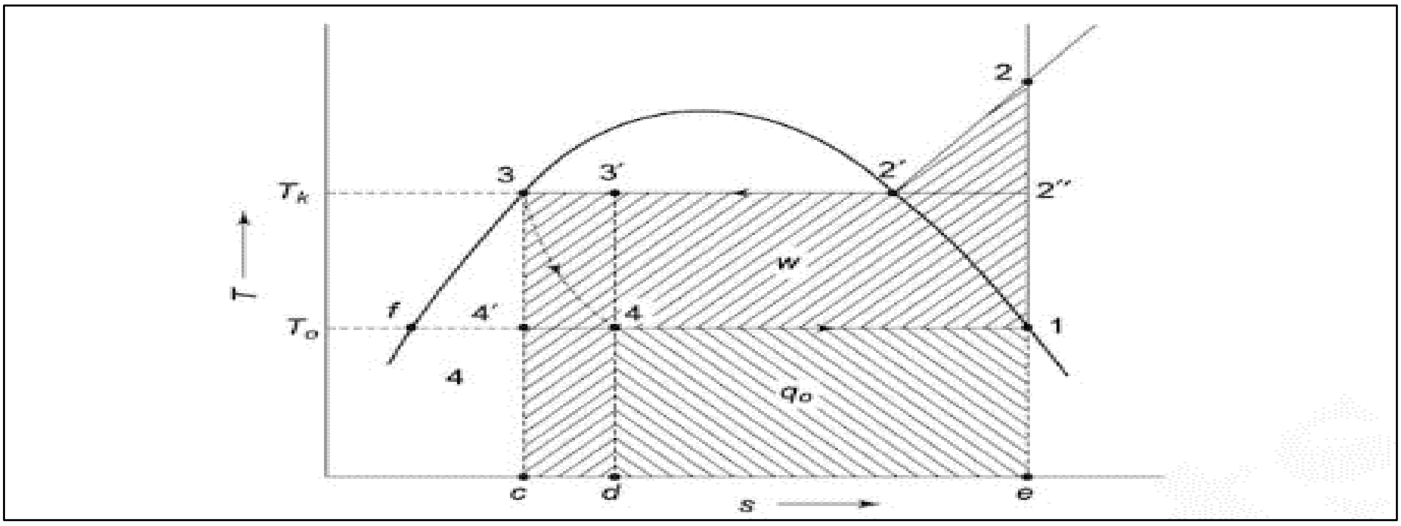

Fig 1 Vapour Compression Cycle on T-s Diagram

The vapor compression cycle differs from the reversed Carnot cycle in three specific aspects, as described below.

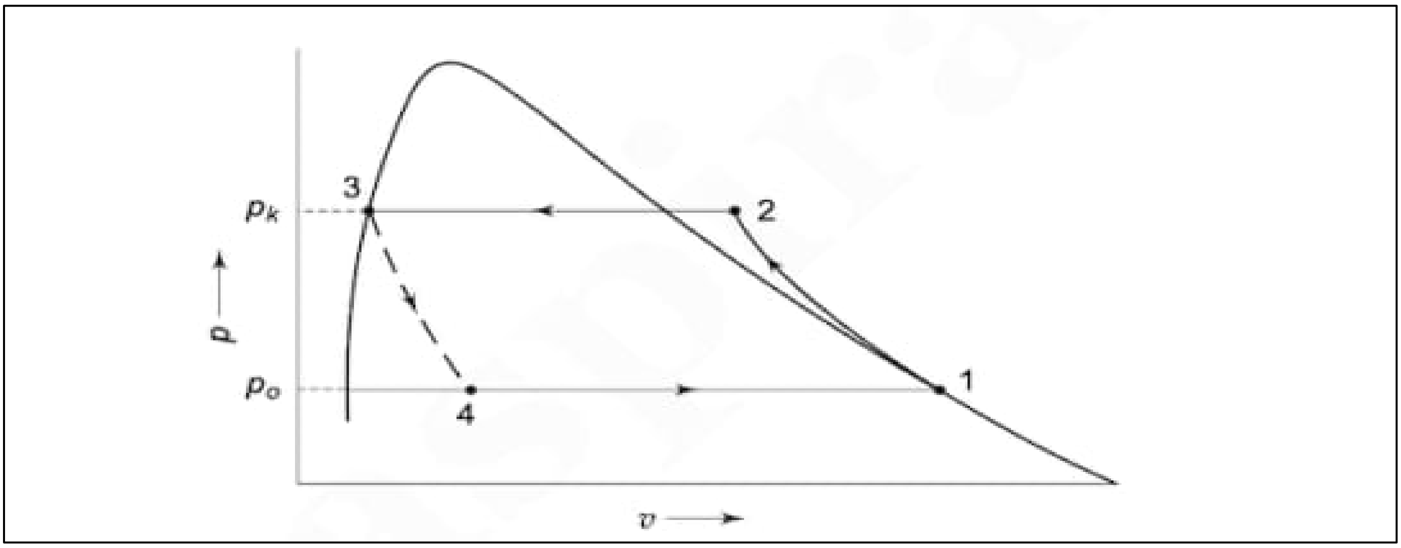

Fig 2 Vapour Compression Cycle on p-v Diagram

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Consequently, the theoretical coefficient of performance (COP) for the vapor compression cycle is less than that of the reversed Carnot cycle. Despite this, it is the most comparable to the Carnot cycle among refrigeration systems, with a COP that approaches the Carnot limit [46].

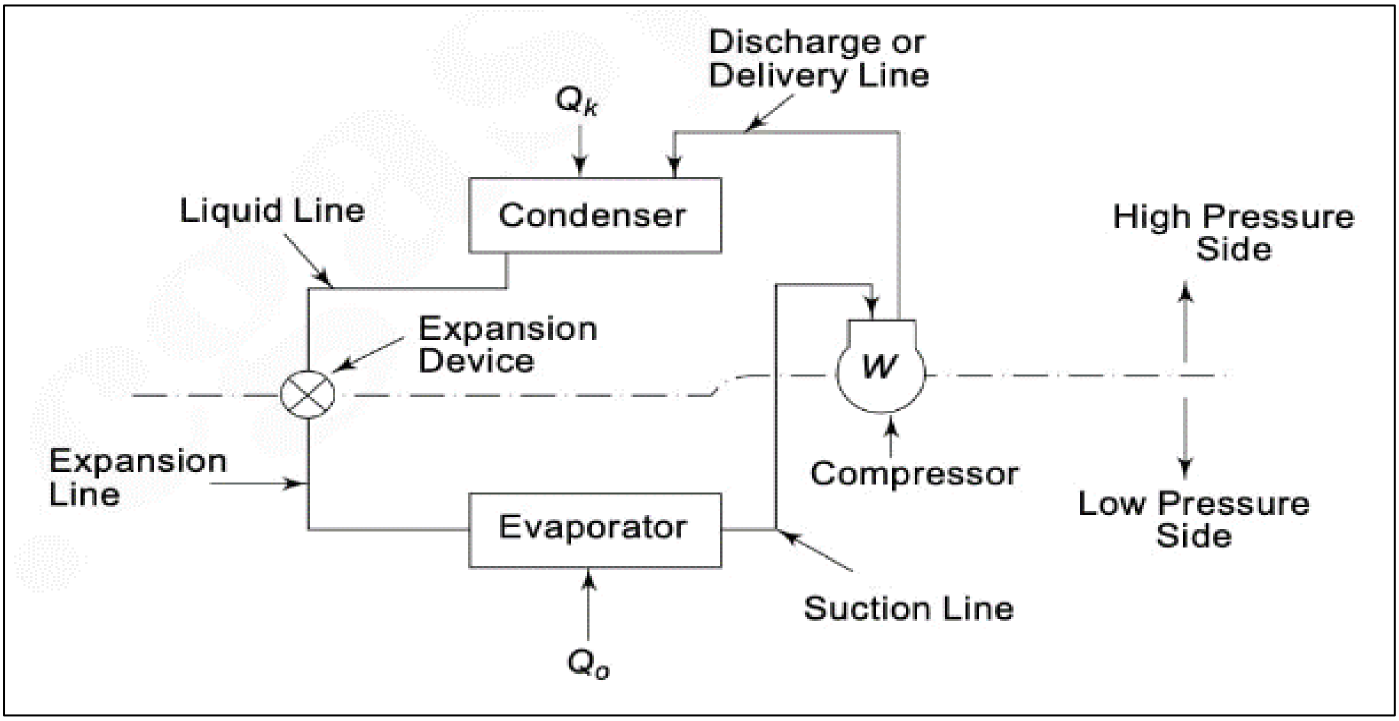

Fig 3 Vapor Compression System

III. NANOFLUID

➢ *Preparation of Nano-Refrigerants*

The synthesis of nano-refrigerants and the preparation of stable nanofluids have been significant areas of research. In the one-step method, nanoparticles are produced and simultaneously dispersed in the base fluid using various techniques, highlighting the need to prevent particle agglomeration to reduce settling issues. Alternatively, the two-step method, known for its simplicity and lower cost, is more widely used, as depicted in Fig. 2. Nanoparticles often used in these fluids include metals like copper, nickel, and aluminum, along with metal oxides such as Al_2O_3, TiO_2, CuO, and SiO_2. Factors like particle type, size, concentration, shape, and preparation methods are critical for achieving optimal performance in refrigeration systems. Section 6 provides further discussion on migration and aggregation behaviors. Peng et al. [46] used an orbital incubator shaker to disperse nanoparticles in a refrigerant, preventing evaporation. They prepared a CuO-R113 nano-refrigerant combined with TiO_2 using a 6-hour ultrasonication process, which successfully stabilized the suspension for up to 12 hours, preventing sedimentation.

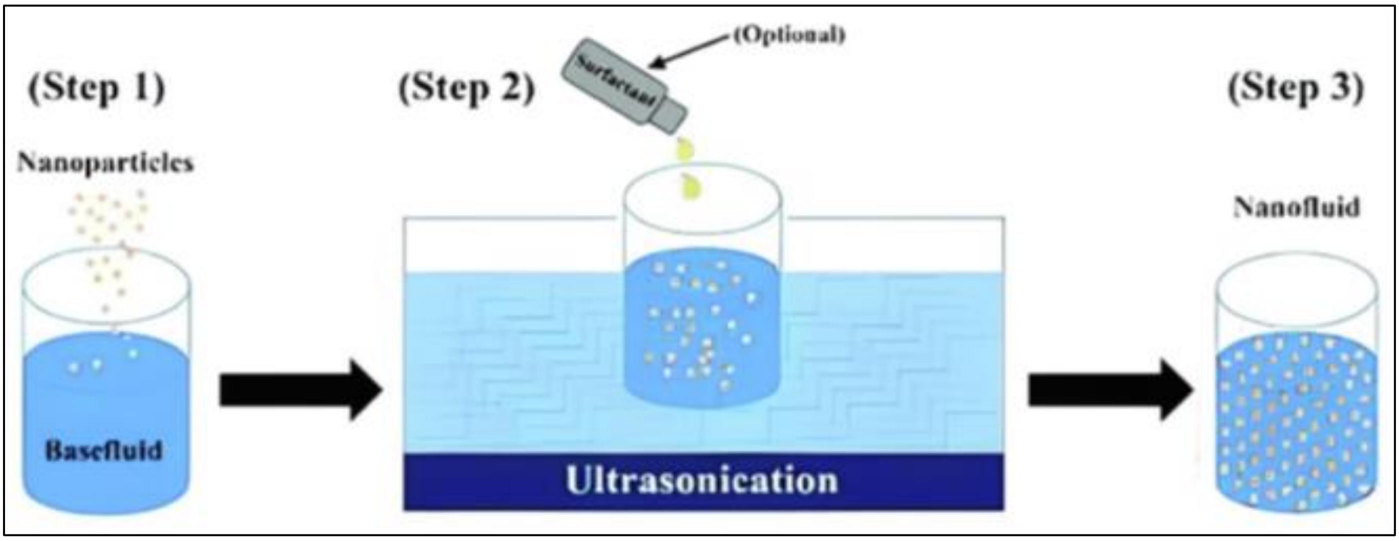

Fig 4 Two-Step Liquid State Nano-Refrigerant Preparation Technique

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➢ *Development of Nano-Refrigerants and Nano-Lubricants*

Nanoparticles are utilized in vapor compression refrigeration (VCR) systems to enhance efficiency, forming nano-lubricants and nano-refrigerants. In nano-lubricants, nanoparticles are mixed with oil to reduce compressor power consumption, while nano-refrigerants feature particles evenly dispersed within the base refrigerant, improving thermophysical and tribological properties (35, 36, 37). Typically, up to 50% of the lubricant remains in the compressor, with the evaporator and dryer using 20% each, and the condenser and hoses utilizing 10% (HVAC Equipment Manufacturer Data). Nano-refrigerants primarily enhance heat absorption, while nano-lubricants improve compressor efficiency through better tribological performance (38, 39).Two main research approaches focus on nanoparticle integration: direct mixing with refrigerants and suspension in lubricants. Nano-refrigerants improve flow, pool boiling, and condensation heat transfer by enhancing thermal conductivity, reducing the required pumping power. Conversely, nano-lubricants, having a higher nanoparticle concentration, demonstrate superior wear and friction reduction but face challenges due to increased viscosity (39, 40). Optimizing nanoparticle concentration is essential for balancing performance gains with potential drawbacks (40).Early experiments using TiO_2-R134a-MO nano-refrigerants demonstrated improved coefficient of performance (COP) (39). Kedzierski and Gong (41) observed that CuO-POE-R134a nano-lubricants increased pool boiling heat transfer by up to 275%, with even slight thermal conductivity improvements yielding substantial heat transfer gains. Subsequent studies by Bartelt et al. (42) confirmed these findings for R134a-POE mixtures in flow boiling, emphasizing the critical role of nanoparticles in enhancing refrigeration system performance.

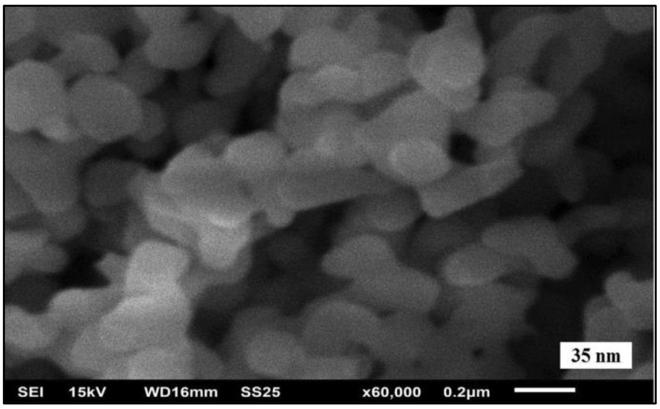

Fig 5 SEM Image Showing Particle Size of Al_2O_3 Nanoparticles

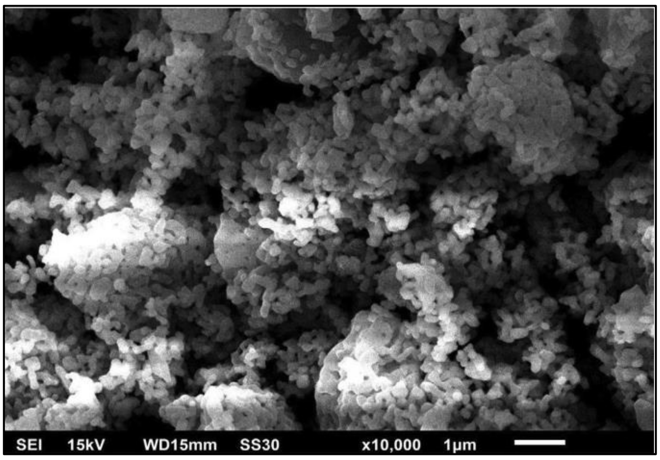

Fig 6 SEM Image Depicting Uniformity of Al_2O_3 Nanoparticles

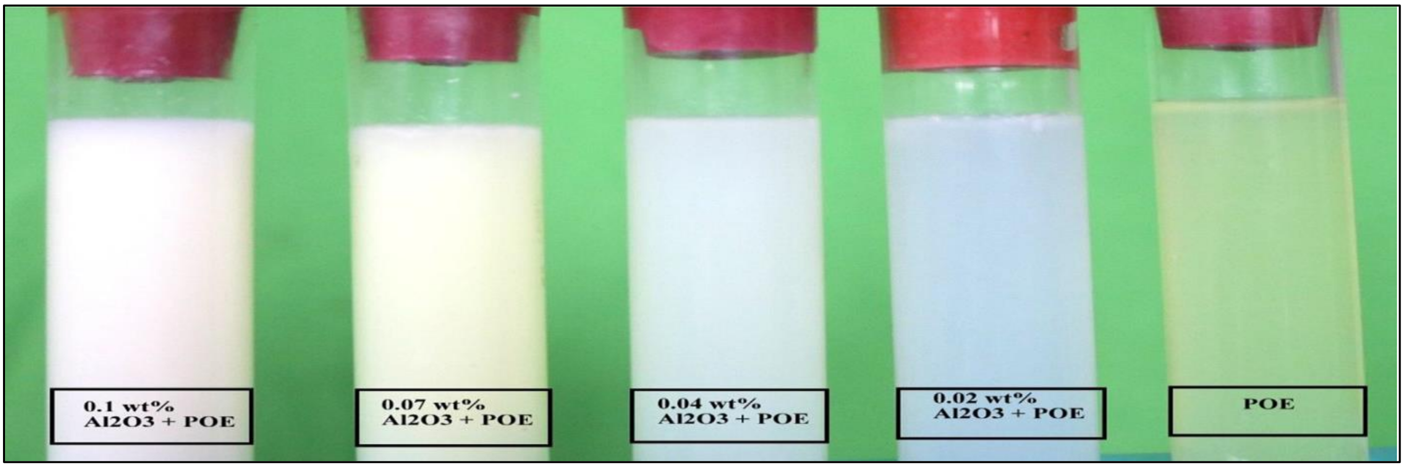

Fig 7 Different Concentration of AL2O3 Nanofluid with POE Oil

IV. PERFORMANCE ENHANCEMENT OF NANOFLUID

➢ *COP Discussion*

The incorporation of nanofluids greatly enhanced the performance of the refrigeration system. Among the refrigerants tested, R600a showed superior results compared to R134a. When Al_2O_3 nanoparticles were added to R134a-POE-based nanofluids, the C.O.P. increased by 19.38% at 0.02 weight percent, 22.44% at 0.04 weight percent, 29.5% at 0.07 weight percent, and 29.5% at 0.1 weight percent. The system using R600a-MO-based nanofluids outperformed R134a-POE. While pure R600a provided better performance than R134a, the R600a-MO mixture achieved a C.O.P. increase of 3% at 0.02, 0.04, 0.07, and 10.25 weight percent of Al_2O_3, with the peak improvement reaching 14.95% at 0.1 weight percent. The highest C.O.P. of 2.69 was observed with the R600a-MO-based nanofluid, with a noticeable difference in performance improvement compared to the R134a-POE nanofluid.[47].

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➢ *Power Consumption*

An experiment conducted with pure R600a refrigerant showed a significant reduction in power consumption. The power usage was measured in watts over a 24-hour period, similar to how the Coefficient of Performance (C.O.P.) is evaluated. The inclusion of nanofluid further contributed to lower electricity usage in the refrigeration system. When Al2O3-R134a-POE-based nanofluid was used at mass fractions of 0.02 wt%, 0.04 wt%, 0.07 wt%, and 0.1 wt%, power consumption decreased by 6.7%, 13.51%, 15.63%, and 25.16%, respectively. In the case of Al2O3-R600a-MO, the reductions were 8.76%, 10.04%, 11.21%, and 21.4% at the same mass fractions. The greatest power reduction, 28.7%, was achieved with Al2O3-R600a-MO nanofluid at a 0.1 wt% mass fraction. [48].

V. FUTURE SCOPE

This research uses numerical and simulation techniques, but experimental studies are needed to validate the performance of nano-refrigerants and energy efficiency in actual cooling systems, which are not included in this paper.

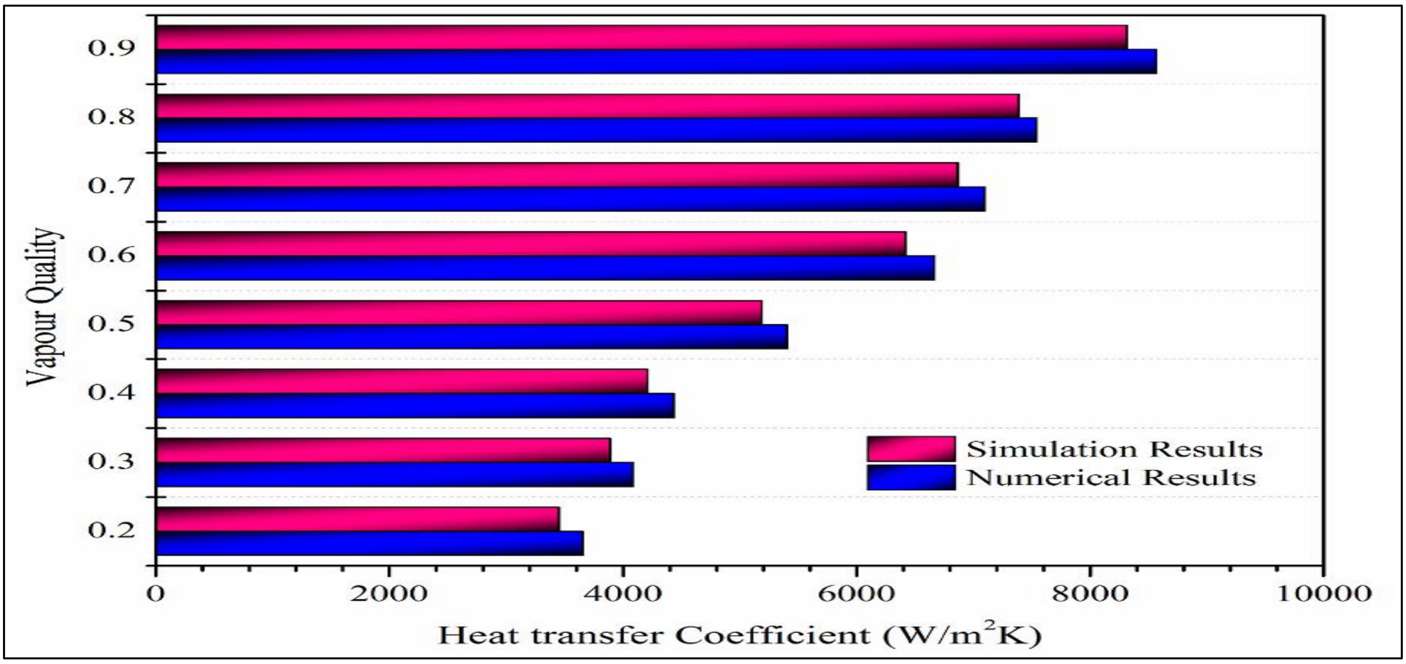

Fig 8 Differences between Numerical and Simulation Results

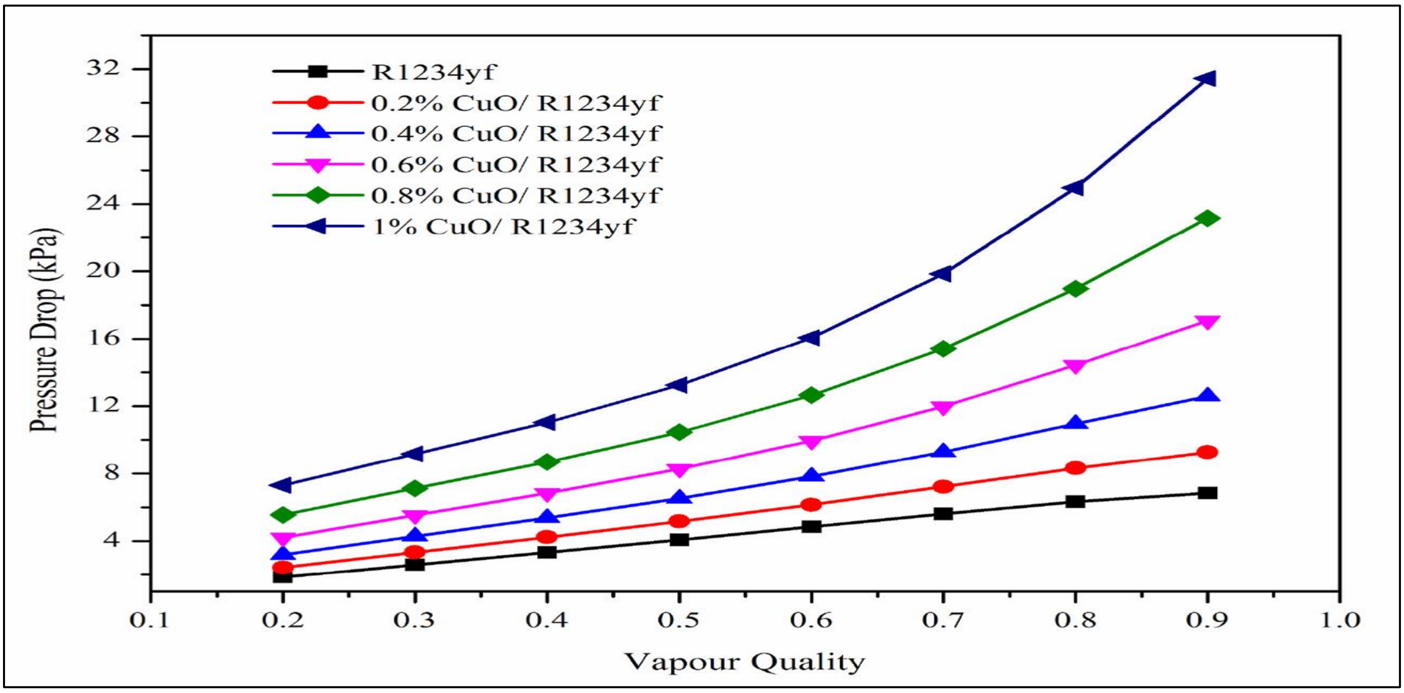

Fig 9 A Comparison of Numerical and Simulation Results for 0.2% CuO/R1234yf.

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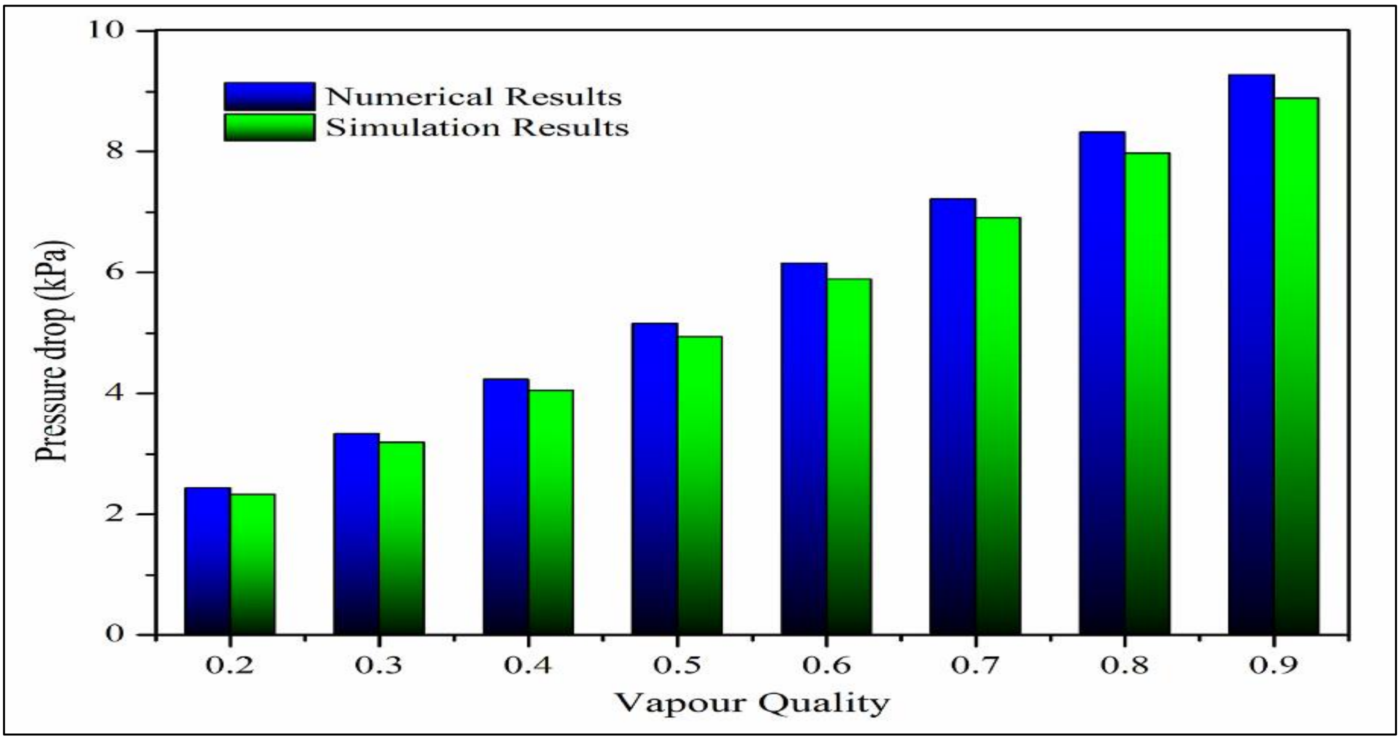

Fig 10 SEM Image Illustrating the Uniformity of Al_2O_3 Nanoparticles

The scope of current research is confined to lower concentrations and smaller nanoparticle sizes. Future investigations could broaden the focus to include higher concentrations, diverse nanoparticle shapes, and varying sizes within the refrigerant.

VI. CONCLUSION

In conclusion, the integration of nanoparticles into vapor compression systems offers a promising approach to enhancing energy efficiency and system performance. Nanoparticles, when dispersed in the refrigerant, can modify its thermophysical properties—such as thermal conductivity, viscosity, and surface tension—resulting in improved heat transfer and reduced compressor workload. These improvements lead to lower energy consumption, which is essential for minimizing the environmental impact of refrigeration and air conditioning. Furthermore, nanoparticles help maintain the long-term stability of refrigerants, ensuring sustained system performance and contributing to the overall durability of vapor compression systems. This technology also holds the potential for reducing the size and cost of systems, making it an appealing option for industries seeking more sustainable and cost-effective solutions. However, there are challenges to overcome, including ensuring the stability of nanoparticles, preventing clogging, and developing compatible lubricants for efficient operation.

In summary, the use of nanoparticles in vapor compression systems shows significant promise for advancing cooling technologies. With further research and development, it can provide energy-efficient, environmentally friendly, and economically viable solutions for a variety of industries moving forward.

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