



REVIEW PAPER

Performance enhancement of vapour compression refrigeration systems using eco-friendly refrigerants and nanoparticles: A review

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Abstract

The use of refrigeration systems accounts for a large share of global energy consumption; hence, there is a need for efficient and environmentally friendly cooling systems. Traditional HFC refrigerants, which, despite having an ODP of zero, have very high GWPs, have prompted the search for low-GWP alternatives. At the same time, the application of nanoparticles to refrigerants and lubricants (nano-refrigerants) is becoming increasingly popular as a promising approach to increase the efficiency of vapor-compression refrigeration systems (VCRS). The addition of nanoparticles with high thermal conductivity improves heat transfer, enhances the efficiency of compressor lubrication, reduces frictional losses and power consumption, and improves COP. This review discusses recent advances in the development of low-GWP and nano-refrigerants, focusing specifically on nanoparticle materials, their thermophysical properties, and their influence on refrigeration system performance.

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Abbreviations

CFCs	Chlorofluorocarbons
COP	Coefficient of performance
CNT	Carbon nanotubes
GNP	Graphene nanoplatelets
Gr	Graphite
GWP	Global warming potential
HC	Hydrocarbons
HFCs	Hydrofluorocarbons
HFO	Hydrofluoroolefin
HCFCs	Hydrochlorofluorocarbons
HTC	Heat transfer coefficient
LPG	Liquefied petroleum gas
LCA	Life-cycle assessment
MWCNT	Multi-walled carbon nanotubes
ODP	Ozone depletion potential
POE	Polyol ester
TEWI	Total equivalent warming impact

1. Introduction

Energy conservation in vapour-compression refrigeration systems (VCRSs) has become an important challenge due to their high global energy consumption. This has led to energy efficiency becoming a research area of interest at present. The most recent trends in research have focused on nano-lubricants and nano-refrigerants, in which nanoparticles are added to compressor lubricants or refrigerants to increase heat transfer rates, improve lubrication, reduce friction losses, and decrease compressor power consumption. A Vapour-compression refrigeration system transfers heat from a low-temperature region to a high-temperature region. It is widely used in domestic, commercial, and industrial applications due to its high efficiency, reliability, and simplicity. Since its invention by Jacob Perkins in 1834, this technology has been continuously improved to enhance its energy efficiency and environmental sustainability. A nanofluid is developed by adding nanoscale particles into a base fluid. Some commonly

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used nanoparticles include Al_2O_3 , TiO_2 , CuO , SiO_2 , Fe_3O_4 , graphene, and carbon nanotubes, and refrigerants and compressor lubricants are base fluids. Hybrid nanofluids

containing more than one type of nanoparticle have recently attracted interest due to their improved thermophysical properties.

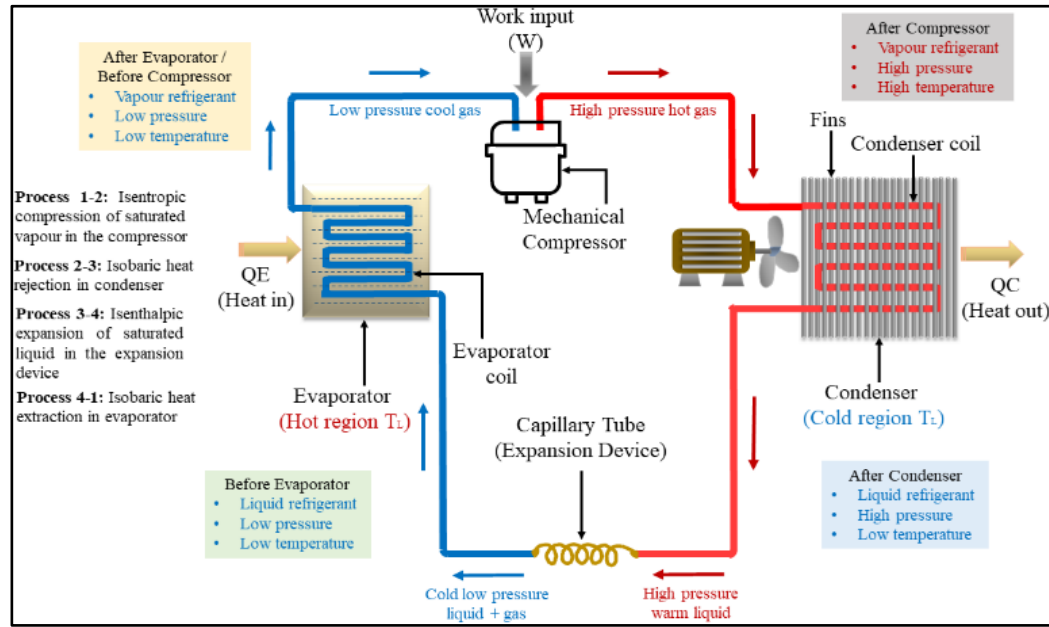


Figure 1: Systematic diagram of VCRS

Figure 1 shows the schematic diagram of the VCR system. The Global Warming Potential (GWP) and Ozone Depleting Potential (ODP) of commonly used refrigerants like hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), and chlorofluorocarbons (CFCs) are summarized in

Table 1. These refrigerants are commonly used in residential and industrial cooling systems. There have been many developments of GWP-free, ODP-free, and nanoparticle-added refrigerants for sustainable cooling systems.

Table 1: Comparison of GWP and ODP Values of HFC, HCFC, and CFC Refrigerants.

Refrigerant				Chemical formula	GWP Value	ODP Value
Designation	Common / Trade Name	Chemical Name	Family			
R11	Freon-11	Trichlorofluoromethane	CFC	CFCl_3	3990	
R12	Freon-12	Dichlorodifluoromethane	CFC	CF_2Cl_2	8400	00.9.9
R22	Freon-22	Chlorodifluoromethane	HCFC	CF_2HCl	1680	0.056
R408A	FX-10	ASHRAE	HCFC	R125/R143a/R22	2650	-
R401A	MP39	ASHRAE	HCFC	R22/R152a/R124	965	-
R32	Methylene fluoride	Difluoromethane	HFC	CH_2F_2	644	0
R125	Pentafluoroethane	Pentafluoroethane	HFC	CF_3CHF_2	2795	0
R134a	Tetrafluoroethane	Tetrafluoroethane	HFC	$\text{CH}_3\text{CH}_2\text{F}$	1300	0

CFCs and HCFCs are the leading causes of climate change and the depletion of the ozone layer, as they have high GWP values and, for CFCs, high ODP values. This means that the substances should be phased out from refrigeration and air conditioning as they are subject to international environmental constraints. HFCs were introduced later as an alternative to these substances due to their zero ODP and lower GWP compared to CFCs and HCFCs. However, some commonly used HFCs have high GWPs, leading to greenhouse gas emissions into the atmosphere. The average pressure values at the evaporator and condenser inlets can be used to determine the evaporating and condensing temperatures under saturated conditions, respectively. The condenser subcooling (SC_k) and evaporator superheating (SH_{ev}) can be found using Eqs. (1) and (2), respectively. The cooling capacity (Q_{ev}) using the

isentropic expansion process can be found using Eq. (3). The compressor volumetric efficiency (η_v) and global efficiency (η_{global}) can be found using Equations (4) and (5), respectively, considering that the specific volume of the refrigerant in the compressor is the same as that at the suction point. The transducer in the refrigeration test rig will provide the refrigerant mass flow rate ($\dot{m}_{\text{ref}}$), discharge temperature (T_{dis}), and power consumption (P_c).

$$\text{SH}_{\text{ev}} = T_{\text{ev,o}} - T_{\text{ev,sat}} \quad (1)$$

$$\text{SC}_k = T_{k,\text{sat}} - T_{k,o} \quad (2)$$

$$Q_{\text{ev}} = \dot{m}_{\text{ref}}(h_{\text{ev,o}} - h_{\text{ev,i}}) = \dot{m}_{\text{ref}}\Delta h_{\text{ev}} \quad (3)$$

$$\eta_v = \frac{\dot{m}_{\text{ref}}V_{\text{comp,i}}}{V_G} \quad (4)$$

$$\eta_G = \frac{P_{\text{comp}}}{\dot{m}_{\text{ref}}W_s} \quad (5)$$

1.1 Refrigerant mass flow rate

A Coriolis mass flow meter was installed in the refrigeration laboratory to measure the refrigerant mass flow rate, an important parameter for determining system performance. The refrigerant mass flow rate depends on several factors, as shown in Equation (6). Geometric displacement of the compressor (volumetric capacity, V_G) depends on the compressor dimensions, such as piston stroke, cylinder bore, and number of cylinders, and hence the displacement volume (cm^3). The speed of the compressor (N) depends on the frequency of the electrical supply and the compressor's mechanical characteristics. When the electrical frequency is 50 Hz, the compressor speed is maintained at the same operating speed (rpm).

$$m_{\text{ref}} = \frac{\eta_v \cdot V_G}{V_{\text{comp},i}} = \frac{\eta_v \cdot V_G \cdot N}{V_{\text{comp},i} 60} \quad (6)$$

Thus, the mass flow rate of each refrigerant, for a given compressor geometry and rotation speed, is determined by the product of the refrigerant's volumetric efficiency and specific volume at the compressor suction. The smaller the refrigerant's specific suction volume and the greater its volumetric efficiency, the larger the refrigerant mass flow rate.

1.2 Compressor power consumption

The electrical power input to the compressor is measured directly with a digital wattmeter. The compressor power input is expressed by Equation (7) in terms of the refrigerant mass flow rate (m_{ref}), the isentropic specific compression work (W_s), and the overall compressor efficiency (η_G).

$$P_{\text{comp}} = \frac{m_{\text{ref}} \cdot W_s}{\eta_G} \quad (7)$$

1.3 Discharge temperature

The discharge temperature of a compressor is one of the key operating variables that depend on the compression process. Other variables include the refrigerant's thermophysical properties, suction temperature and pressure, compression ratio, and the cooling of the compressor crankcase. Variations in the above-mentioned parameters influence the discharge temperature, which in turn affects the lubricant's stability, the compressor's efficiency, and the performance of the refrigeration cycle.

1.4 Cooling capacity

Cooling capacity of Vapour compression system can be expressed as a multiplication between the mass flow rate of the refrigerant (m_{ref}) provided by the compressor and the specific refrigeration effect (Δh_{ev}), where the specific refrigeration effect is a function of the evaporating temperature and the state of the refrigerant at the inlet and the outlet of the evaporator, which is shown in Equation (3). By combining equations (3) and (6), it can be written that the cooling capacity depends on

the geometric swept volume flow rate of the compressor (V_G), the volumetric efficiency of the compressor (η_v), and the volumetric refrigeration effect (q_v).

$$Q_{\text{ev}} = \eta_v \cdot V_G \cdot q_v \quad (8)$$

1.5 Coefficient of performance

One of the key parameters characterizing the efficiency of a refrigeration system is the coefficient of performance (COP), calculated as the cooling capacity (Q_{ev}) divided by the compressor power consumption (P_c). Based on Equations (3) and (7), the COP can be expressed as the ratio of the specific cooling effect to the specific compression work, as given by Equation (9). An increase in COP indicates improved energy efficiency and, consequently, improved performance of the refrigeration system.

$$\text{COP} = \frac{Q_{\text{ev}}}{P_{\text{comp}}} = \frac{m_{\text{ref}} \cdot \Delta h_{\text{ev}}}{m_{\text{ref}} \cdot \frac{W_s}{\eta_G}} = \frac{\eta_G \cdot \Delta h_{\text{ev}}}{W_s} \quad (9)$$

2. Literature Review



Figure 2: Articles published over time on nano lubricants in Scopus and the Web of Science database.

The review mainly focuses on environmentally friendly refrigerants due to their environmental impact. Thus, an extensive analysis of the environmentally friendly refrigerants is needed. The study on natural refrigerants emphasizes minimizing environmental impact. The search conducted on the Scopus and Web of Science databases using the keywords "Environmentally friendly refrigerants", "Nanoparticles", "Global warming potential", and "Coefficient of performance" has resulted in 2869 and 2306 papers related to VCRES in the period from 2003 to 2026, as depicted in the bar graph in Figure 2.

2.1 Environmentally Sustainable Refrigerant Selection and Evaluation

HFC refrigerants are being phased out due to their high GWP, despite their favorable thermodynamic properties. Thus, increasing attention is being paid to the use of low-GWP refrigerants with zero ODP. Among these refrigerants is the

R290/R600a hydrocarbon mixture, which can be used as an alternative to R134a, with reduced power consumption, up to 3.6% higher COP, and good compatibility with POE oil. Nevertheless, the flammability of this mixture requires some safety precautions [1]. A comprehensive survey of environmentally acceptable alternatives to halogenated refrigerants was conducted to identify and implement sustainable options that reduce the environmental impact of traditional refrigerants. Since 2008, there has been successful development of HFO refrigerants with lower GWP and better environmental performance than traditional halogenated refrigerants [2]. Experimental comparison of R152a, R1234yf, and R134a revealed that R1234yf had operating properties similar to R134a but a 10% lower cooling capacity and a 15% lower COP. Nevertheless, its much lower GWP makes this refrigerant a potential alternative to R134a. With the phasing out of high-GWP HFC refrigerants, low-GWP HC and HFO refrigerants become sustainable alternatives for future use [3]. A comprehensive review revealed that the use of nano-refrigerants and nano-lubricants improves the thermophysical and tribological characteristics of working fluids and increases their heat-transfer capacity, lubrication, and overall system performance by reducing energy consumption [4]. Studies on natural refrigerants have continued, especially in the field of HC refrigerants. The paper reveals that HCs are promising substitutes for conventional halogenated refrigerants due to their favorable environmental characteristics (zero ODP and negligible GWP). However, the high flammability of HCs limits their widespread use, necessitating safety measures, system changes, and careful application [5]. In order to confirm the research findings, two environmental effects of natural and artificial refrigerants (ODP and GWP) have been discussed in detail. The authors proposed a parametric quantitative model to select appropriate refrigerants based on thermodynamic efficiency and environmental sustainability. In addition, the rules and regulations of international environmental agreements (Kyoto Protocol, Paris Agreement, Montreal Protocol, and F-gas regulation) have been analyzed to assess the feasibility of new refrigerants in the future [6], [7]. Carnot COP and experimental analysis of an appropriate mixture of refrigerants for domestic refrigeration systems. It was discovered that certain refrigerant mixtures can increase system efficiency and maintain satisfactory operating parameters.

Furthermore, the authors suggested that when specific operating conditions are provided, using several smaller compressors, each with a different refrigerant mixture, is closer to the ideal cycle [8]. Also, the study conducted a temperature distribution analysis to determine the influence of refrigerant blends on compressor performance. It developed a new compressor design to increase the efficiency of the home refrigeration system [8]. An experimental analysis of a residential refrigerator's performance was conducted by varying the refrigerant charge and capillary tube length. For this study, HC refrigerant mixtures of R290 and R600a in different ratios were used. The results showed that R436A (56% R290 and 44% R600a) performs better than R134a. This mixture increased refrigeration performance and reduced pull-down time. Consequently, based on these results, the

researchers concluded that R436A is an environmentally friendly alternative to R134a for domestic refrigeration applications [9].

While considerable attention has been paid to alternative refrigerants in the past few decades, the combination of low-GWP refrigerants, nano-refrigerants, and lubricant compatibility has not received sufficient attention. In this connection, the refrigerants R32, R290, R600a, R1234yf, and R1234ze provide zero ODP, low GWP, and higher COP, and a hybrid absorption-compression system can be more efficient. Moreover, the research has shown that the R134a/LPG mixture performs better than pure R134a in terms of COP and refrigeration capacity, but LPG flammability remains a major problem [10], [11]. Pure HC and hydrocarbon-blend refrigerants are being considered as replacements for halogenated refrigerants. Conventional refrigerants have higher GWP and ODP, which is a problem in the study. As the results show, hydrocarbon refrigerants and their mixtures are feasible as environmentally friendly refrigerants due to their zero ODP and low GWP. However, for their efficient use in refrigeration applications, their safety needs to be ensured. The performance effects of nano-lubricants and nano-refrigerants on energy efficiency and performance of refrigeration cycles were investigated. Based on their research, it is possible to state that adding nanoparticles to lubricant oil and refrigerants improves thermophysical properties and heat-transfer efficiency, and reduces energy consumption in the refrigeration cycle [13]. A numerical model has been developed to predict the performance of mini-scale VCRRS for various refrigerants. Various refrigerants have been analyzed for their thermodynamic and environmental performance. R290 has shown better performance than other refrigerants and could be chosen as an alternative to R134a because of its high energy efficiency and low environmental impact. The scientists have considered several configurations of heat exchanger tube diameters in order to analyze their impact on system efficiency. These differences are explained by the various systems' designs, operating conditions, and modeling approaches. The numerical results are consistent with early experimental and simulated studies [14]. While considerable advancements have been made in the development of low-GWP refrigerants, the combination of eco-friendly and nano-refrigerants with compatible lubricants remains an untapped area. Refrigerants such as R32, R290, R600a, R1234yf, and R1234ze have zero ODP, low GWP, and higher COP, and hybrid absorption-compression systems have increased energy efficiency. In addition, the R134a-LPG mixture has shown higher COP and refrigeration capacity, and lower lubricant loss, than R134a under optimal conditions, although the flammability of LPG remains a major constraint [15]. The theoretical research was conducted to identify potential alternatives to R134a for car air conditioners. The assessment of R134a was based on its thermodynamic and environmental properties compared with R290, R600a, R1234yf, and other potential refrigerants. The research showed that R1234yf is the most preferred replacement for R134a due to its similar performance, significantly lower GWP, and compatibility with car air-conditioning systems. R290 and R600a have favorable thermodynamic and environmental properties, but their high

flammability makes them unsuitable for use in automobile air-conditioning systems [16].

2.2 Economic Viability of Low-GWP Refrigerants in Vapour Compression Refrigeration Systems

A theoretical analysis approach based on R744 (CO₂) was established to evaluate the performance of the refrigeration system. [17]. To enhance the energy efficiency and performance of the CO₂/NH₃ cascade refrigeration system, energy performance and multi-objective optimization were studied. [18]. The effects of superheat/sub-cooling of a VCRS on energy performance and cost-effectiveness were analyzed. This analysis was conducted to evaluate the effects of these conditions on overall performance, energy use, efficiency, and system operating costs. [19]. A theoretical model was developed to analyze the energy, exergy, and economic performance of eight refrigerants in a multistage VCRS. By varying four design parameters, an optimization approach was adopted to improve the system's efficiency by maximizing the COP [20]. A thermo-economic model to optimize the performance of a cascade VCRS using an R744/R134a refrigerant mixture was developed. Based on thermodynamic and economic principles, the proposed model was applied to assess and optimize system performance. [21]. The economic evaluation was carried out using an electric heater alongside the heat pump system, with either R134a or R290 refrigerant, to establish the return on investment for each type [22]. The energy efficiency, exergy efficiency, and economic evaluation of the VCRS were calculated using a steady-state model with R152a, R600a, and R1234ze refrigerants. Using a multi-objective optimization approach, the most favorable operating conditions and the optimal refrigerant choice for system performance have been established [23].

2.3 Environmentally Friendly Refrigerants for VCRS

To determine the energy performance of R1234yf as a drop-in replacement for R134a, a steady-state model and experiments have been developed. To analyze the suitability of R1234yf as a refrigerant in Vapour-compression applications, critical performance parameters such as COP, compressor efficiency, and evaporator cooling capacity have been investigated [24]. Based on capillary tube expansion and R744 as the refrigerant, a steady-state model for a heat pump system has been developed. Using the proposed model, system performance has been evaluated, and the minimum capillary tube diameter required under different operating conditions has been determined [25]. With R744 as the refrigerant, a dynamic analysis model has been developed to examine the performance of the heat pump system, including the solar evaporator and expansion valve assembly. To analyze the thermal behavior and performance of the components, the model has been evaluated under both transient and steady-state conditions [26]. The energy performance of several refrigerants has been evaluated using experimental studies and a steady-state model [24].

The potential of R1234yf as a substitute refrigerant for VCRS initially designed for R134a was investigated using a dynamic

model. To evaluate the performance of R1234yf in terms of operational performance and suitability under different conditions, the research involved the characterization and analysis of the system's control strategy [27]. To investigate the effect of expansion valve tuning on the performance of a small-scale solar-assisted heat pump system, a steady-state model was developed, and an experiment was conducted. To assess the effects of expansion valve tuning on system performance, the research focused on key parameters, including pressure variations, compressor power consumption, COP, refrigerant mass flow rate, and enthalpy difference [28]. To determine the best refrigerant for a direct-expansion solar-assisted heat pump system, a steady-state model was developed. To identify the most suitable refrigerant to improve system performance, the study considered the effects of operating parameters, including COP, TEWI, ambient temperature, solar radiation intensity, and wind speed [29]. A steady-state model of a VCRS is established to evaluate the environmental and energy efficiency of R1234yf as a replacement for R134a. This research work aims to determine whether the two refrigerants can be used effectively in environmentally friendly refrigeration systems based on their thermodynamic properties [30]. To investigate the transient response of a direct-expansion solar-assisted heat pump system using R744 refrigerant to a sudden change in solar radiation, a dynamic model is developed using two approaches [31]. Environmental, energy, and exergy performance of different refrigerants, such as R290, R1234yf, and R744, was evaluated using the developed model. In terms of their environmental friendliness and thermodynamic efficiency, the study aimed to determine whether the refrigerants could be used in Vapour-compression refrigeration cycles [32]. To evaluate the energy and exergy performance of R513A as a drop-in replacement for R134a, a steady-state model was developed. To evaluate the refrigeration capacity, COP, rate of exergy destruction, and exergy efficiency of R513A and R134a, the study considered the system's full operating range [33].

3. Influence of Nanofluids Addition on the Performance of Vapour Compression Refrigeration Systems

CuO-based nano-lubricants have shown considerable promise in improving the performance of refrigeration systems. The incorporation of 0.1 vol.% CuO nanoparticles into PAG lubricant increased the efficiency of refrigeration systems by increasing COP and freezer performance, minimizing power requirements, and improving heat transfer in the condenser and evaporator [34].

3.1 Effect of Al₂O₃ Nanoparticles on Refrigeration System Performance

The performance of various Al₂O₃-based nano-refrigerants has been analyzed in terms of factors such as coefficient of performance, compressor power, heat transfer rate, and discharge temperature. From among the various refrigerants under study (R134a, R430A, R12, R436A, and R600a), R600a-Al₂O₃ nano-refrigerant proved to be the most effective in terms of coefficient of performance, whereas R12 and

R134a had the least compressor power consumption [35]. In addition, an experimental analysis was conducted regarding the influence of nanofluid properties (density, viscosity, and thermal conductivity) on the coefficient of performance of a refrigeration cycle [36].

3.2 Effect of Multi-Walled Carbon Nanotubes on Refrigeration System Performance

MWCNTs have high thermal conductivity and can therefore be used as effective additives in nano-refrigerants. This results in improved thermal conductivity and flow-boiling heat transfer in refrigerants, thereby increasing their efficiency [37].

3.3 Effect of SiO₂ Nanoparticles on Refrigeration System Performance

Although many researchers have studied SiO₂ nanoparticles, their use in refrigeration systems remains limited. Studies indicate that SiO₂-based nano-refrigerants increase the heat transfer coefficient by up to 163% at a nanoparticle concentration of 0.4% [38].

3.4 Effect of TiO₂ Nanoparticles on Refrigeration System Performance

TiO₂-based nano-refrigerants have been found to enhance the performance of the VCR system. Though an increase in TiO₂ concentration increased the power requirement of the compressor, there was an improvement in freezing capacity of the refrigerant mixture (R600a/TiO₂) and refrigerant mixture (R134a/TiO₂) compared to the pure refrigerant, showing that these are suitable for improving the efficiency of refrigeration systems [39]. TiO₂ nano-refrigerants have proved to be quite effective in enhancing the performance of refrigeration systems [40]. The study by Patel et al. [41] focused on advancements in Vapour-compression refrigeration systems that use environmentally friendly refrigerants and those combined with nanoparticles. It was noted that GWP-free refrigerants such as R290, R600a, and R1234yf could be used in place of common HFCs without affecting refrigeration performance. In addition, nanoparticles such as Al₂O₃, TiO₂, CuO, SiO₂, and MWCNTs help improve heat transfer, increase COP, and reduce compressor energy consumption. Further research is needed in this field.

4. Discussions

Based on the literature review, the use of low-GWP refrigerants and nanoparticles enhances the efficiency and sustainability of Vapour-compression refrigeration systems (VCRS). As depicted in Figure 2 below, research has increased over the last two decades, especially after 2015, due to environmental policies encouraging alternatives to high-GWP refrigerants. Some of the alternative refrigerants identified are R290, R600a, R1234yf, R1234ze, and R744, which are better replacements for existing refrigerants. Hydrocarbon refrigerants tend to have a 3–10% increase in COP, lower

power consumption, and a smaller refrigerant charge. On the other hand, the flammability aspect of hydrocarbon refrigerants poses a significant challenge for their mass adoption. Nanoparticle-laden refrigerants and lubricants help improve system performance through enhanced thermal conductivity, improved heat transfer, improved compressor lubrication, and reduced friction losses. Among the tested nanoparticles, Al₂O₃, TiO₂, CuO, SiO₂, and MWCNTs showed the most promise, with TiO₂ nanoparticles achieving COP increases of up to 60% under optimal conditions. High nanoparticle concentrations increase viscosity and pressure loss, thereby lowering efficiency; therefore, optimizing nanoparticle concentration is a priority. As a whole, the use of low-GWP refrigerants with nanoparticle-laden lubricants seems like an effective way towards efficient refrigeration systems. However, some issues have to be solved first.

5. Conclusion

Recent advancements in environmentally friendly and nanoparticle-enhanced refrigerants for VCRS were thoroughly reviewed in this paper. The following findings can be made in light of the literature review:

- HFC refrigerants, even with low ODP, have quickly been phased out because of their high GWP.
- While maintaining similar refrigeration properties, low-GWP refrigerants such as R290, R600a, R1234yf, R1234ze, and R744 have proven to be very good alternatives.
- Even with a higher COP, reduced compressor power utilization, and more efficient energy use, the flammability of hydrocarbons remains a problem that warrants stronger safety measures.
- Nanoparticles improve the thermophysical properties of lubricants by increasing their thermal conductivity and heat transfer, reducing friction, and optimizing compressor lubrication.
- The greatest potential for improvement among the nanoparticles tested is observed in Al₂O₃, TiO₂, CuO, SiO₂, and MWCNTs; TiO₂ and Al₂O₃ yield substantial improvements in refrigeration efficiency.
- The density of nanoparticles greatly influences the efficiency of the refrigeration system. Whereas optimum density greatly increases the coefficient of performance, excess density of nanoparticles results in losses in viscosity and pressure.
- One way to develop an environmentally sustainable refrigeration system that reduces greenhouse gas emissions and power consumption is to integrate low-GWP refrigerants with nano-lubricants.

6. Future Scope

Even if the development of eco-friendly nano-refrigerants has advanced significantly, there are still several research avenues that could be explored in the future:

- Long-term experimentation is necessary to study the stability, settling behavior, and longevity of nanoparticle-

containing refrigerants in real-world applications.

- To improve system reliability, compatibility studies of nanoparticles with compressors, seals, lubricants, and other refrigerant components are needed.
- Hybrid nanofluids containing multiple nanoparticles require further investigation to achieve greater benefits in thermal conductivity and refrigeration performance.
- Further research is necessary to optimize the size, shape, and concentration of nanoparticles across different refrigerants and operating conditions.
- Advanced numerical simulations and CFD modeling will help elucidate the flow behavior of refrigerants, nanoparticle transport, and boiling heat transfer.

To create extremely energy-efficient, ecologically sustainable, and financially feasible cooling systems, future refrigeration technologies are anticipated to incorporate low-GWP refrigerants, cutting-edge nanomaterials, intelligent control strategies, and renewable energy sources.

Credit to the author's contribution statement

Sameer Kumar: Conceptualization, Methodology, Investigation, Formal analysis, Writing-reviewing

Rehan Khan: Writing, reviewing and editing, Project supervision, Data collection,

Abhishek Singh: Conceptualization, Data curation, Writing-reviewing and editing, Project supervision

Ghanshyam Das: Methodology, Data curation, Investigation, Formal analysis, editing

Uttam Kumar: Methodology, Data collection, Investigation, Formal analysis

Shailesh Kumar Pandey: Editing

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