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Thermo-physical properties, heat transfer characteristics and performance of nano-enhanced refrigerants: A review

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Abstract

To boost the efficacy of a refrigeration system, researchers have imported nanoparticles into refrigerants in recent years. This paper comprehensively reviewed the properties, heat transfer performance, and system performance of nano-added refrigerants in recent years. This article likewise assists with recognizing the gap in past research works and explores the possibilities for additional work. Refrigerant R134a charged with the nanoparticles TiO_2 has the highest value of coefficient of performance which is 63.5% higher than that of Al_2O_3 nanoparticle charged R134a. Charging of the nano-refrigerants has enhanced the heat transfer performance of vapour compression refrigeration systems, particularly in the pool and nucleate boiling heat transfer. The heat transfer coefficient of R134a-based nano-refrigerant is enhanced by 42% and 30.2% with CuO and TiO_2 nanoparticles respectively. The inclusions of nanomaterials, concerning their physical phenomena, influencing the vapour compression refrigeration system are confined in this paper.

Keywords: Nano-refrigerants; Vapour compression refrigeration; Heat transfer enhancement; Coefficient of performance; Coefficient of heat transfer

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1. Introduction

Energy is the main input to the social, economic, industrial, and technological development of every country. Its demand is increasing with the rise in the population and enhancement in the standards of living. The energy crisis and environmental issues are the major problems facing all over the world. In these problems, the refrigeration system takes a vital role. In the current situation, the refrigeration system consumes around 20 % of the total production of energy. The substances used in these systems are causing the ozone layer thinning and increase the temperature of the atmosphere. Based on recent reports, in India, 23%

Nomenclature

c_p – specific heat capacity
k – thermal conductivity
Nu – Nusselt number
r_p – radius of nanoparticles
Re – Reynolds number
t – thickness of the interfacial layer

Greek symbols

μ – viscosity
ρ – density
ϕ – volume fraction of the nanoparticle

Subscripts and Superscripts

l – interfacial layer
nr – nano-refrigerant
p – nanoparticle
r – refrigerant

Abbreviations and Acronyms

CHT – coefficient of heat transfer
COP – coefficient of performance
GWP – global warming potential
HC – hydrocarbons
HFO – hydro fluoro olefin
HT – heat transfer
HTF – heat transfer fluid
MO – mineral oil
ODP – ozone depletion potential
PAG – polyalkyleneglycol
PDT – pull downtime
POE – polyol ester
PVD – physical vapour deposition
RE – refrigerating effect
VCR – vapour compression refrigeration

of the overall energy is utilized by the refrigerator and 2% by the air conditioner [1]. In Poland, the energy consumption of refrigerators and freezers accounts for about 5% of the total electricity consumption in households, while the energy consumption of air conditioners accounts for about 4% of the total electricity consumption. According to Eurostat data, in 2020 the energy consumption for heating, ventilation, and air conditioning (HVAC) equipment accounted for approximately 33% of the total energy consumption in buildings in the European Union [2]. The latest analysis indicated that since increasing household appliances the energy utilization by the refrigeration system rose continuously. In various countries around the globe, the Government has put forward policies related to energy efficiency to minimize the usage of energy; consequently, the usage of refrigeration systems becomes economical and nature friendly [3]. Reducing the energy and environmental effect of substances used in refrigerant systems lead to new research. Nanotechnology also involves a new kind of research. Nanotechnology makes it possible to produce metal or metal oxide with sizes ranging from 1 to 100 nm called nanoparticles. By the inclusion of nanomaterials in the standard fluid, the thermal conductivity (k) of the fluid could be improved [4]. The volume concentration and the type of nanoparticles used are the key factors for improvement in heat transfer (HT) performance [5]. Generally, nanoparticles are the build-up of metals, oxides, or carbides, due to their small size and large surface area. Nanofluids should have better thermal properties, less sedimentation, and decline clogging flow lines [6].

Refrigeration is the action of reducing the temperature of a confined area by removing heat. In the vapour compression refrigeration (VCR) system, the phase change of the working fluid will produce the cooling effect and the performance of these systems could be enhanced by using a water-cooled condenser and by using a heat exchanger at the end of the compressor [7]. Nowadays refrigeration becomes a human necessity, but it leads to global warming. For refrigeration purposes, varieties of refrigerators and various compositions of refrigerants were used [3].

Choi and Eastman [8] developed a novel kind of HTF by adding nanoparticles to the base fluid. These conceptual studies indicated that the HT is enhanced extremely when nanoparticles are added to base fluids. Nanofluids are engineering fluids that possess a high specific surface area. Due to this property, nanofluids have a higher transfer capacity between particles and fluids. It also possesses high dispersion stability, reduced particle clogging, and reduced pumping power [9–12]. Nanoparticles act differently from their parental materials in properties such as molecular interaction and nature of reaction for mass and energy usage. The thermophysical properties such as thermal conductivity, convective HT, viscosity, and thermal diffusivity of standard fluids are enlarged by nanoparticles [13].

Nano-refrigerant is a type of nanofluid that is prepared by nanoparticles and is perfectly mixed with the base refrigerant. Since it has better thermo-physical properties, the rate of HT can be boosted. Because of these, the use of nano-refrigerant in the refrigeration system can develop a compact and lighter system; raise the 'k' of the refrigerant and upgrade the HT features of the entire thermodynamic system [14, 15]. The utilization of nanoparticles in the base fluid could boost the miscibility between the refrigerant and lubricant [16, 17]. The nanoparticles in the nano-refrigerant remain to put up for more time than microparticles and remain in suspension almost forever [18]. Also, the nanoparticle increases the solubility between the lubricants and refrigerants [19] (Fig. 1).

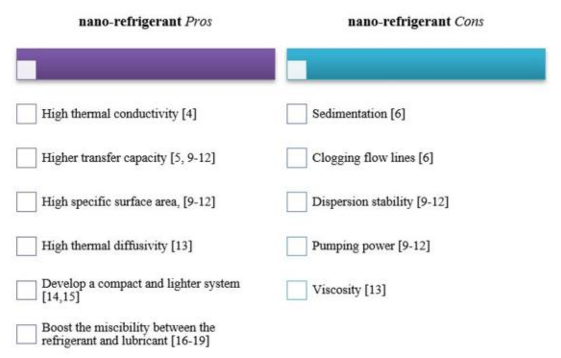

Fig. 1. Pros and cons of nano-refrigerant.

The goal of the current article is to present an extensive review of the development of nano-refrigerants for different categories of refrigerant-based and their performance. This paper explores and analyses the types of nano-refrigerants in refrigeration systems. The properties such as HT performance based on the HT coefficient; system efficacy in respect of coefficient of performance (COP); energy efficiency and exergy efficiency are reviewed in this article.

2. Preparation of nano-refrigerant

The nano-refrigerant is prepared by dispersing the nanoparticles spread over the refrigerant, and then it straight away boosts up the refrigerant thermal properties and hence improves the refrigeration system performance [3]. In preparation for nano-enhanced refrigerant, there are two ways to add nanoparticles to the working fluid. It is known as the charging of nanoparticles. Based on this there are two categories, one is nano-refrigerant and the other one is nano-lubricant. In nano-refrigerant, the nanoparticles are dispersed directly to the refrigerant, whereas in nano-lubricant the particles are added to the compressor's lubricant. This is shown in Fig. 2.

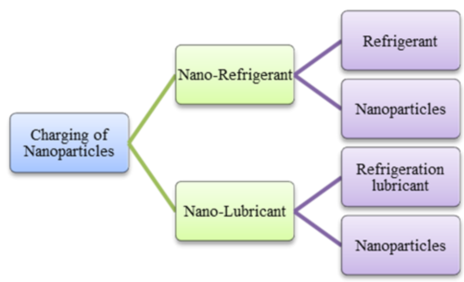

Fig. 2. Methods of charging nanoparticles.

Nano-refrigerants and nano-lubricants are alike in the way of operation; meanwhile, there are remarkable differences between both. The refrigeration system that works with nano-refrigerant will have a boost in the heat transport features in contrast to tribology characteristics. While nano-lubricant provides an improvement as far as tribology as the nanoparticles are more massed in the compressor lubricant contrasted with the refrigerant. The nanoparticle addition of both refrigerant and lubricant was demonstrated to raise the energy efficiency in the system remarkably. The nano refrigerant is prepared in two ways: a single-stage technique and a double-stage technique.

2.1. Single-stage technique

The single-stage technique combines the preparation of nanoparticles with the blend of nano-refrigerants in a single stage, with nanoparticles formed directly by PVD or liquid chemical treatment [3].

2.2. Double-stage technique

The double-stage technique is the step-by-step process of the production of nano-refrigerant from the preparation of nanoparticles. The nanoparticles are involved in each step, mainly in the action of dying, storage, and transportation. Ultrasonic stirring or additions of surfactants to the fluids are employed to reduce particle collection and enhance dispersion capacity. To ensure the proper blending of nanomaterial with standard fluid, an ultrasonic agitator or higher shear mixing devices were used [3].

Mohan et al. [20] also adopted the double-stage technique to prepare the nano-refrigerant with a probe sonicator. They produced nanoparticles into dry powder and were kept in the hot oven at 80ºC for 24 hrs. At that point, nanoparticles completely blended in with polyalkyleneglycol utilizing an ultrasonic vibrator with a frequency of about 40 Hz. Subhedar et al. [21] prepared the samples by two-step method with oleic acid as the surfactant. To get the stable nano-refrigerant they used sonics and made a VCX500 probe sonicator to apply ultrasonic agitation force. The sonication was done for 1 hr at the frequency of 50 Hz to homogenize the 1 L sample. Chauhan et al. [22] used a double-stage technique with no surfactant added all over the making process of nano-refrigerant. This process was finished by employing the magnetic agitator for 2 hrs followed by ultrasonic homogenization of nano-refrigerant for a determined period. Subramani and Prakash [23] used two unique techniques for sonication for the preparation of nano-refrigerants. Firstly, the ultrasonic bath technique was utilized with a vortex blender as the initial stage and this method failed in the sedimentation test. Secondly, they used a probe sonicator with a magnetic stirrer.

The double-stage technique is a commonly used process in the combination of nano-refrigerants by blending base fluid with industrially accessible nanoparticles acquired from various chemical, physical, and mechanical processes like grinding, milling, and sol-gel and vapor phase techniques [3].

3. Analysis of nano-refrigerants concerning the thermo-physical properties

The thermo-physical properties are necessary for estimating the nano-refrigerant's efficiency. The viscosity, density, thermal conductivity, surface tension, specific heat, and latent heat are some of the important thermal and physical properties of the fluid. The thermophysical properties were studied numerically using some relations. The values of nano-refrigerant's thermal conductivity were determined by Sitprasert et al. [24] correlation

$$k_{nr} = \frac{(k_p - k_l)\phi k_l[2\beta^3 - \beta^3 + 1] + (k_p + 2k_l)\beta_1^3[\phi\beta^3(k_l - k_r) + k_r]}{\beta_1^3(k_p + 2k_l) - (k_p - k_l)\phi[\beta_1^3 + \beta^3 - 1]}, \quad (1)$$

where: $\beta = 1 + \frac{t}{r_p}$, $\beta_1 = 1 + \frac{t}{2r_p}$, $k_l = C\frac{t}{r_p}k_p$, k_P is the conductivity of the nanoparticle, k_l is the thermal conductivity of the base liquid, ϕ is the volume fraction of the nanoparticle.

The Brinkman model [25] was used to measure the dynamic viscosity of nano-refrigerant as follows:

$$\mu_{nr} = \mu_r \frac{1}{(1 - \phi)^{0.25}}, \quad (2)$$

where: μ_r is the viscosity of the base refrigerant.

Pak and Cho's [26] relationship was used to calculate the density of nano-refrigerant:

$$\rho_{nr} = \phi\rho_p + (1 - \phi)\rho_r, \tag{3}$$

where: ρ_p is the density of the nanoparticle, ρ_r is the density of the base refrigerant.

Pak and Cho's [26] relationship may be used to determine the specific heat of nano-refrigerant

$$c_{p,nr} = \phi c_{p,p} + (1 - \phi)\, c_{p,r}. \tag{4}$$

3.1. Viscosity of the nano-refrigerant

The concentration of nanoparticles and temperature has a significant effect on the viscosity of the nano-refrigerants. According to the studies, the viscosity on the discharged side is lesser than on the suction side. The rise in the fluid temperature causes lowered cohesive and adhesive forces between the molecule and would lead to the reduction in fluid viscosity [27]. Mahbubul et al. [28] identified the dynamic viscosity of R134a/Al_2O_3 with enhancement in its value by 28.58%. A similar result was obtained by Zawawi et al. [29] and found that the viscosity was enhanced with volume concentration and declined with temperature. Chauhan et al. [22] studied the viscosity of R134a/TiO_2/POE (where POE - polyol ester) and discovered that the maximum value was 0.38 mPa·s on the suction side and 0.2 mPa·s on the discharge side at 0.3% TiO_2 concentration. The viscosity test conducted by Ajayi et al. [30] revealed that the existence of nanoparticles in the refrigerants reduces the viscosity. The reduced viscosity affected the heat generation directly and reduced its value. According to Ambhore et al. [3], increasing nanoparticle concentration increases nano-refrigerant viscosity.

The viscosity of the nano-refrigerant was also affected by the viscosity of the base refrigerant, according to the report by Subhedar et al. [21] studies show that the volume concentration of nanoparticles depends on viscosity. The viscosity of nano-refrigerant was increased with the volume fraction of nanomaterials present in it. They were used by Anton Paar's viscometerto determine the viscosity. The viscosity of Al_2O_3/R141b nano-refrigerant was evaluated by Soheel et al. [31] using the Brinkman model. They found that the viscosity and degradation declined with increasing temperature, depending on the quantity of nanoparticles. The kinematic viscosity of the nano-refrigerant is directly affecting the overall energy consumption. When the viscosity value is low, then the energy losses are also less [30].

3.2. Thermal conductivity of the nano-refrigerant

The thermal conductivity (k) value of the fluid is related to convective HT and boiling coefficients. Therefore, it is one of the most influential thermo-physical properties of a nano-refrigerant. As a result, recent studies have placed a strong emphasis on thermal conductivity, with non-linear thermal conductivity enhancement being verified as the temperature rises [22]. Based on the studies Brownian motion of nano-sized particles gets raised with the increase in temperature contributing to the rise in micro-convective HT. This process enhanced the thermal conductivity finally [32].

Jiang et al. [33] identified that the enhancement in the nanomaterial concentration causes thermal conductivity improvement. Mahbubul et al. [28] studied the thermal conductivity of R134a/Al_2O_3 and they found that its value increased by 28.58%. Likewise, Patil et al. [34] discovered that the effective value of k declined with the particle size. According to Zawawi et al. [29], the thermal conductivity of nanoparticles is affected by their volume concentration and temperature. The value of k was improved with the concentration of nanomaterial and it declined with temperature. Liu and Hu. [35] found that increasing the volume fraction of TiO_2 increased the value of k of R134a/TiO_2. When 5% of the volume concentration of TiO_2 was introduced to the standard fluid, the value of k increased by 30%. They also discovered that as the temperature rose, so did the thermal conductivity. Soheel et al. [31] explored the thermal conductivity of the R134a-based nano-refrigerant. They used Al_2O_3, SiO_2, ZrO_2, and CNT as nano inhibitors with different mass concentrations. From these, they identified that the thermal conductivity was improved with the nanomaterial concentration in the refrigerant. Figure 3 depicts the thermal conductivity of R134a nano-refrigerant with various nanoparticles at different concentrations. From the figure, it is clear that R134a with SiO_2 gives more thermal conductivity than that of the other nanoparticles such as Al_2O_3, ZrO, and CNT.

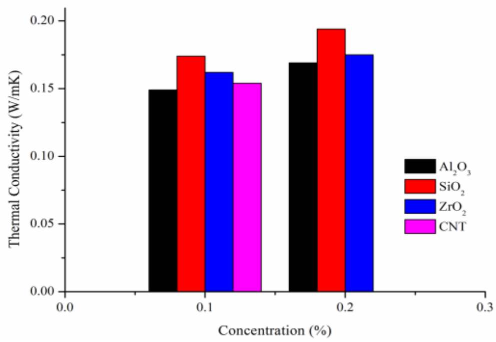

Fig. 3. Thermal conductivity of different R134a-based nano-refrigerants [31].

Ambhore et al. [3] concluded that conventional refrigerants have lower thermal conductivities than nano-refrigerants. The thermal conductivity of R134a/TiO_2/POE was obtained by Chauhan et al. [22] and their highest values were 0.107 W/(m K) and 0.125 W/(m K) at 0.3 % concentration of nanoparticle on suction and discharge sides respectively. According to Alawi et al. [36], variation in the value of 'k' of R141b/Al_2O_3 nano-refrigerant is linear with temperature and volume fracture. As per the studies, as the temperature rises, the Brownian motion of nanoparticles and the effect of micro-convection in HT boost up, increasing thermal conductivity [32,37]. At 305 K, Rahman et al. [38] discovered that the values of 'k' of R407c/SWCNT nano-refrigerant were 15.6% higher than the conventional refrigerant.

3.3. Nano-refrigerant specific heat capacity and latent heat

According to Ajayi et al. [39] the existence of bio-based nanoparticles in the fluid enhanced the value of c_p and latent heat of the working fluid, resulting in an improvement in heat transportability. When the temperature and volume fraction increase from 10 ºC to 35ºC and 1 vol% to 4 vol% the heat capacity of R141b/Al_2O_3 increases, according to Alawi et al. [36]. They also discovered that the nano-refrigerant had the lowest specific heat value at a particular volume fraction. The lower value of c_p of integrated materials contributed to this reduction. Alawi and Sidik [37] found that the value of c_p of the R141b refrigerant was 2.6% less than the R141b/Al_2O_3 nano-refrigerant. This was because of the enhancement in heat capacity leading to an increase in the system's internal energy. On the other hand, an increase in temperature will result in the variation of the value of liquid around its equilibrium value. This would increase the system's heat capacity since a greater amount of energy would be available. The specific heat capacities of nano-fluids have been reported to be lower than the base fluid [40].

Alawi et al. [36] found that increasing the temperature at the output resulted in a noticeable increase in specific heat. It was discovered that refrigeration systems that used nano-refrigerants were able to have better performance as a result of their higher production temperature. The existence of nanoparticles in the base fluid resulted in a higher output temperature. Hence, the specific heat was known as "the necessary heat to increase the temperature of a unit mass of a substance by one unit of temperature." As a result, any material with a lesser specific heat will produce a greater output temperature with the same amount of heat flow. According to Rahman et al. [38], with the inclusion of nanoparticles, the specific heat of the R407c/SWCNT nano-refrigerant decreased. This is attributable to the SWCNT nanoparticle's lower specific heat. When opposed to R407c refrigerant, the R407c/SWCNT nano-refrigerant reduced the value of c_p by 4.1% and 4.93% at 283 K and 308 K, respectively. They also found out that the system's internal energy was enhanced with an increase in the specific heat values.

3.4. Density

Solid particles have a much greater density than fluids, so the solid-fluid suspension has more density, in contrast, to the base fluid. If the concentration of nanomaterials in the standard fluid rises, the temperature rises and the density falls linearly [22]. According to Mahbubul et al. [28], the density of R134a/Al_2O_3 increased by 11%. Chauhan et al. [22] found that the density of the nano-refrigerant R134a/TiO_2/POE was observed to be greatest at 0.3% nanoparticle concentration, with values of 1 660 kg/m^3 and 1 370 kg/m^3 at 10ºC suction and 80ºC discharge temperature respectively.

As the temperature and volume fraction rose, Alawi et al. [36] discovered that the density of R141b/Al_2O_3 nano-refrigerant and R141b refrigerant decreased. The atoms of the refrigerant begin to vibrate as the temperature rises, increasing the refrigerant volume while decreasing the density.

4. HT performance with the nanoparticles

Researchers used a variety of approaches to improve the refrigeration system's HT efficiency in the experiments. Active and passive methods for improving HT efficiency have been identified [41]. HT was improved by an active technique of HT enhancement methods. This involved surface area modification and boundary layer adjustments. Heat transport was improved in passive methods by optimizing the thermal properties of working fluids [42]. Nano-refrigeration is a passive process for improving the system's HT. This is because, in nano-refrigeration, the nanoparticles are added to the refrigerants for improving the thermal properties of working fluids.

Bartelt et al. [43] researched on R134a-CuO nano-refrigerant and discovered that adding a 1% volume concentration of CuO improved the coefficient of Heat transfer (CHT) by 42%. Coumaressin and Palaniradja [44] found that the heat fluxes changed from 10 kW/m^2 to 40 kW/m^2 when CuO concentration varied from 0.5% to 1% and particle diameter from 10 nm to 70 nm. Furthermore, it was discovered that the evaporative CHT boost sup when CuO nano particle was added up to 0.55% concentration after that it was declining.

Besides, Coumaressin and Palaniradja [44] used GAMBIT software to illustrate an augmentation in the CHT for the R134a/CuO nano-refrigerant. Soheel et al. [31] considered the HT performance of CuO/R134a nano-refrigerant using a two folds channels heat exchanger. They have seen progress in HT characteristics. They identified that HT coefficient increased to 0.55% of the convergence of nano molecules and decreases for all properties. Also, they found out that the higher value of the CHT was 1 755.8 W/(m^{2}K) for a 5% volume concentration of nanoparticles.

According to Ajayi et al. [39], the inclusion of bio-based nanoparticles had a beneficial impact on the heat-carrying efficiency of the evaporator and condenser. They discovered that adding nanoparticles improves intermolecular reactions and alters fluids into heat-carrying fluids with high heat capacity. This ensures that the materials behave in such a manner that the fluids' capability to absorb a massive amount of heat from the requisite area per unit degree rise in temperature is increased, and so heat is transferred to the heat sink through enhanced intermolecular interaction.

The studies of Eid et al. [45] identified that the CHT of nano-refrigerant decreases with the rise in nanomaterials concentration. They also discovered that by raising the concentration of Al_2O_3 nanoparticles in R134a refrigerant to 0.25%, the CHT could be doubled and that when the concentration exceeded this amount, the coefficient was decreased.

Naas [46] identified that the CHT was enhanced by 50 % by adding TiO_2 nanoparticles from 0.05% to 1% to the R134 refrigerant. The HT characteristics of R134a/TiO_2 nano-refrigerant were investigated by Sanukrishna et al. [47]. They discovered that when the nanoparticle concentration is 1.5%, the CHT increases by 30.2%. Pasha [48] investigated the evaporator's variance, the Nusselt number's relationship to the Reynolds number, as well as the heat flux and nanoparticle concentration in the refrigeration device. The rise in Nusselt (Nu) number leads to the rise in Reynolds (Re) number, heat flux, and nanoparticle concentration up to 0.5, according to the research. They also discovered that the value of Nu was increased by a maximum of 67% while the value of Re were increased by 98% of its lowest value.

4.1. Flow condensation

Sheikholeslami et al. [49] investigated the flow within a horizontal plain tube in an experimental environment for identifying the condensation HT of nano-added refrigerant. They used R600a/POE/CuO nano-refrigerant. They identified that the coefficient of condensation HT depends on vapour quality, mass flux, and nanoparticle concentration in the working fluid. The value of HT was enhanced by vapour quality because of the reduction of liquid film thickness on the inner wall of the tube which lessened the internal thermal resistance. Another work of these authors [50] investigated the condensation activities inside a horizontal tube for identifying the development of entropy and loss of exergy in nano-refrigerant. They deduced that increasing mass flux, vapour quality, or nanoparticle concentration resulted in a modest increase in the development of entropy on account of HT. This is because the condensation CHT and Nu numbers have improved. They also discovered that nanoparticles did not affect the Bejan number, which was a ground-breaking research finding. The Bejan number is the ratio of HT entropy to overall HT and friction.

4.2. Pool boiling

Pool boiling is a technique of transferring heat on the surface into a huge matter of stagnant liquid. This is a form of boiling process in which the surface temperature is moderately higher than the fluid's saturated temperature. The nucleation and subsequent development of fluid vapour bubbles on the surface, followed by their growth from the surface, define this mechanism. In general, the growth of bubbles in a pool boiling is influenced by temperature, surface type, fluid thermodynamic properties, and surface tension. Pool boiling is used in heat-carrying devices in the process and refrigeration industries as a critical method of HT [51]. The optimum configuration of the evaporator in a refrigeration process necessitates the precise calculation of the refrigerant's pool boiling CHT [52]. HT on pool boiling was investigated by Park and Jung [53,54] using a carbon nanotube–halocarbon refrigerant nanofluid. The experiments were carried out with a 1% volume nanoparticle concentration and a pool temperature of 7°C, and remarkable pool boiling HT augmentation was observed. The study in R113/CNT/ VG68 nano-refrigerant indicated that the improvement of nucleate pool boiling could reach 61% in contrast to without nanotube refrigerant and oil mixture [28]. Peng et al. [55] conducted the pooling boiling HT experiment with R113/diamond nano-refrigerant. They discovered that HT promotion caused by diamond nanoparticle augmentation on pool boiling is higher than nanoparticles of CuO augmentation under related conditions.

The experiments on pool boiling of R141b/TiO_2 nano-refrigerant were done by Trisaksri and Wongwises [56]. They discovered that at strong heat fluxes, the increase in nanoparticle concentration improved pool boiling. Ray et al. [57] studied the pool boiling of R134a on flat copper surfaced with TiO_2 and thin film coating of thickness 100 nm and 200 nm. From this, they identified that the maximum enhancement in CHT was achieved with the 200 nm coating thickness and uncoated copper surface. They also resolved that the improvement in CHT was because of increased surface irregularity and improved dynamic nucleation site concentration. Ray and Bhaumik [58] analyzed the pool boiling of R134a at 100°C on a smooth copper surface coated with a smaller layer of TiO_2 nanoparticles. The boiling HT acquires 87.5% of improvement with the high thickness of TiO_2-coated surface than the surface without copper. They concluded that nanoporosity (*surface roughness* = 12.4 nm), nucleation site density, and area of heating surface influence the improvement of CHT. Kedzierski and Gong [59] established the pool boiling HT characteristics of the R134a/CuO nano-refrigerant. According to the findings, a CuO-based nano-refrigerant would improve HT.

5. Performance studies on refrigeration systems

The performance of the refrigeration system is evaluated by various parameters such as COP, pull downtime (PDT), refrigerating effect (RE), and power consumption. The ratio of the heat consumed by the refrigerated area to the compressor work is known as the COP. The cooling effect is the rate at which heat is removed from a refrigerated space and is proportional to the refrigeration system's cooling ability. The pull-down time is the amount of time it takes to reach a certain temperature in the refrigerated space. By improving the heat absorption rate in the evaporator or lowering the compressor's power, it could be enhanced the refrigeration system's performance.

5.1. Vapour compression refrigeration system

The VCR cycle is a version of the refrigeration system in which a circulating liquid working fluid serves as the channel for absorbing and removing heat from a confined area, producing a cooling effect, and then rejecting the heat to the environment [3]. The performance examination of VCR systems with nano-refrigerant is studied by many researchers. Based on their studies we have comprehensively concluded the results from various researchers.

According to the values of enthalpy at the inlet and outlet of the VCR system elements, the theoretical COP of the system was determined. To identify the system's actual COP, the work absorbed by the compressor and the heat released from the evaporator was used [20]. Figure 4 shows the variation of power consumption with different nano additives to the refrigerants. The power consumption is very less in the case of ZnO nano-sized particles added to the base refrigerant. While the Al_2O_3-added nano-refrigerant takes more power to run the system.

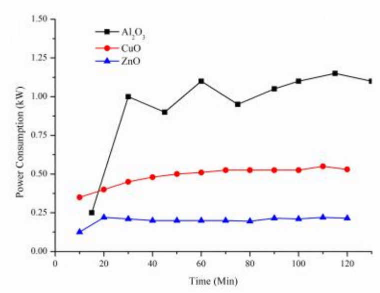

Fig. 4. Power consumption of different R134a-based nano-refrigerants.

Wang et al. [60] conducted the first experiment in the VCR system with nano-added refrigerant in 2003. The researchers discovered that nano-refrigerants improved the refrigeration system's COP and cooling effect.

The capability study of a VCR system was carried out by different analyses. PDT analysis, exergetic analysis, energy utilization analysis, and cooling load analysis were used by Ajayi et al. [30]. The PDT is the amount of time it takes to vary the temperature of the evaporator compartment from ambient to final. According to the PDT analysis, the nano-refrigerant achieves low temperatures three times faster than ordinary refrigerants. Ajayi and his colleagues found that the Al_2O_3-based nano-refrigerant system was more efficient with a lower cooling effect. The impact of R410a/Al_2O_3/MO nano-refrigerant on VCR was analyzed by Peyyala et al. [7]. The compressor exit temperature reduced and the coefficient of performance increased when the nanoparticle concentration increased. The studies of Mohan et al. [20] revealed that the actual COP depends on the evaporator temperature. The actual COP gradually increases as the evaporator temperature increases. Figure 5 indicates the fluctuation of evaporator temperature with time for various nano-refrigerants. From the Fig. 5, it is clear that after a certain time, all nano-refrigerant gives a constant evaporator temperature. The ZnO nanoparticle added to R152a refrigerant attained a very low evaporator temperature and it stabilized very quickly.

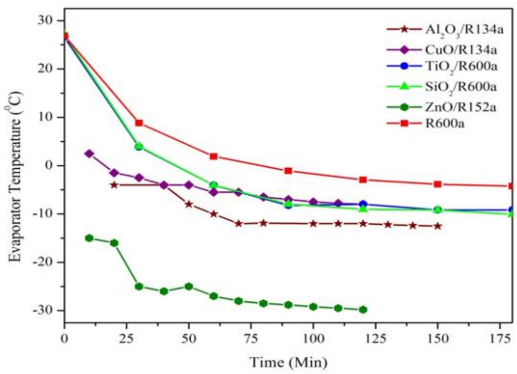

Fig. 5. Evaporator temperature with time for different nano-refrigerant.

The studies of Subhedar et al. [21] had revealed that the compressor power and coefficient of performance depend on the volume concentration of nanoparticles. They found around 27% reductions in compressor power using 0.075 % volume concentration R134a/Al_2O_3/MO nano-refrigerant. Chauhan et al. [22] discovered that as the concentration of TiO_2 increases, the temperature decreases. The lowest temperature of −16.7°C is obtained with 0.3% volume concentration of nanoparticle, whereas it is observed at −13.5°C for the base fluid used. Also, it was identified that freezing capacity depends on nanoparticle concentration. Since at higher concentrations, the drop in evaporator temperature is moderately high, therefore the freezing capacity increased as the TiO_2 concentration increased. Figure 6 shows the dependency of COP, Input power, and freezing capacity with the concentration of nanoparticle addition.

According to Prasad et al. [61] the COP of the system decreases and the energy consumption of the system increases with room temperature. According to Adelekan et al. [62], improving the concentration of nano-particles in the refrigerant or base fluid improves the refrigeration system's efficiency by reducing compressor work and increasing the HT rate. The condenser's performance degrades when a system operates at high pressure in hot and dry conditions.

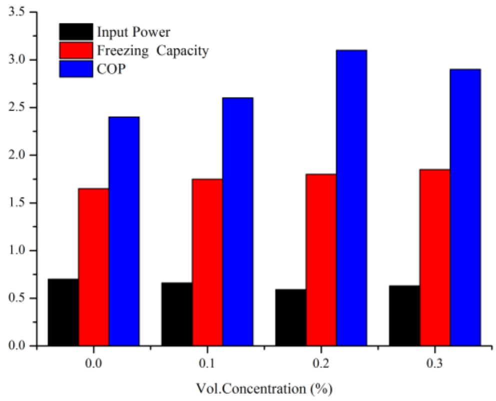

Fig. 6. Variation Input Power, freezing power, and COP with the concentration of TiO_2 in R134a.

The maximum exergy loss with R134a/Al_2O_3 identified by Dhondge and Kalbande [63], occurred in the evaporator and compressor and the values were lies between 36% to 37% of the whole losses in the system. And also, found that the highest sustainability index in R134a with 0.5 nanoparticle concentration. Generally, the exergy analysis revealed that the energy cannot be built nor be demolished; it could be degraded in quality. Exergy analysis can help us figure out what's causing process inefficiencies, where they're coming from, and how big they are. Dhondge and Kalbande [63] found that the evaporator temperature declined the exergy efficiency which means that the cooling efficiency of the system increased and the percent exergy destruction of the compressor decreases as the compressor has to do minimum work for maintaining the maximum temperature inside the evaporator. Table 1 tabulates the overview of performance in the VCR system. According to Yong et al. [64], TiO_2 increases the compatibility of mineral oil and R134a. Figure 7 illustrates the variation of COP with different nanoparticles. From the figure, it is clear that when 0.1 % of TiO_2 nanoparticle was added to R134a gave higher COP.

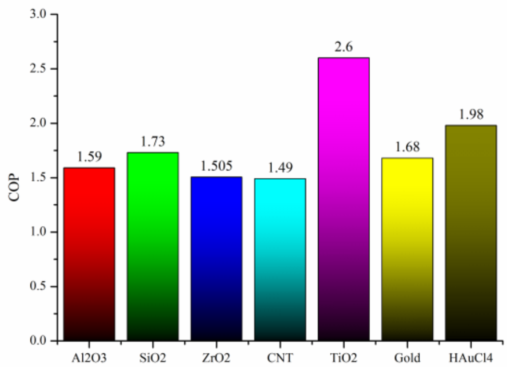

Fig. 7. Variation of COP with different nanoparticles.

Table 1. Summary of performance studies in vapour compression refrigeration system.

Author	Refrigerant	Nanoparticle	Lubrication oil	Main points
Wang et al. [60]	R134a	TiO_2	Mineral oil	• The system's performance was enhanced by the inclusion of nanomaterials in the refrigerant.
Padmanabhan and Palanisamy [65]	R134a, R436A, R436B	TiO_2	Mineral oil, Polyol ester (POE)	• R134a/TiO_2/MO achieve higher COP as compared to R436A/TiO_2/lubricant and R436B/TiO_2/lubricant
Patil et al. [34]	R134a	TiO_2	Polyol ester (POE)	• When 0.1% of nanoparticles are added, energy usage is decreased by 26.1%.
Yong et al. [64]	R134a	TiO_2	Mineral oil	• The energy utilization decreased by 26.1% when 0.1% of nanoparticle concentration and 50 nm particle size.
Chauhan et al. [22]	R134a	TiO_2	Polyol ester (POE)	• At 0.2% concentration, the least compressor power input and greatest COP are obtained. • The compressor uses 15.8% less electricity and the COP increases by 29.1% at 0.2% concentration.
Subramani and Prakesh [23]	R134a	Al_2O_3	Mineral oil	• The freezing capacity has increased, although the power consumption has decreased by 25%.COP was increased by 33%.
Kumar and Elansezhian [66]	R134a	Al_2O_3	Mineral oil	• Improvement in energy absorption by 10.32%.
Raghavalu et al.[68]	R134a	Al_2O_3	Ethylene glycol	• The system's COP increased by 12.08%.
Ajayi et al. [30]	R134a	Al_2O_3	Capella D	• The Al_2O_3 nanoparticles improve the system's freezing capacity. Higher values of exergy were obtained. • The system with nano-refrigerant consumed less power. • The presence of Al_2O_3 nanoparticles enhances the cooling, reduced energy consumption, and improved the performance of the system.
Dhondge and Kalbande [63]	R134a	Al_2O_3	-	• With the inclusion of nanoparticles, the COP rises, improving the system's overall performance.
Subhedar et al. [21]	R134a	Al_2O_3	Mineral oil	• The maximum improvement in COP is around 85% for 0.075% volume concentration of nano-refrigerant. • The highest COP was 3.68 at 0.075% volume concentration. • 27 % of compressor power saved.
Ambhore et al. [3]	R134a	Al_2O_3	-	• The addition of 0.5% of Al_2O_3 nanoparticles will lead to an enhancement in the overall performance.
Mohan et al. [20]	R134a	Gold, $HAuCl_4$, CNT	Polyalkyleneglycol (PAG)	• 31.7 % of enhancement in actual COP was attained with 0.1% Au + 0.005% CNT. • The loss of exergy for 0.1%Au + 0.005%CNT declined by 8%.
Harichandran et al. [68]	R134a	h-BN	Polyolester (POE)	• At 0.3 % volume concentration of nanoparticle, the COP improved by 60%
Peyyala et al. [7]	R140a	Al_2O_3	Mineral oil	• Reduction in compressor exit temp, improvement in COP, energy efficiency ratio, and pressure ratio when the percentages of nanoparticle concentrations were increased.
Pico et al. [69]	R410A	Diamond	Polyol ester (POE)	• Maximum enhancement in COP is 8%. • A reduction in compressor discharge temperature by 4°C causes a reduction in compressor power.
Sabareesh et al. [70]	R12	TiO_2	Mineral oil	• Power consumption of the system declined by 11%. • The COP improved by 17%.
Kumar and Elansezhian [71]	R152a	ZnO	PAG	• At 0.5% ZnO volume, energy consumption decreased by 21%. • Evaporation temperature declined by 6%.
Ajuka et al. [72]	R600a	TiO_2	Mineral oil	• At 1.5% mass concentration of nano addition, COP enhanced by 14.3% • The energy consumption was reduced by 35.15% at a 1.5% mass concentration of nanoparticles.
	LPG	TiO_2	Mineral oil	• The COP increased by 27.6% at 1.5% of mass concentration. • At a 1.5% mass concentration of nanoparticles, the energy consumption declined by 34.6%.

5.2. Domestic refrigeration system

To find a replacement for R134a, Ajayi et al. [39] examined the effect of nanomaterial produced from agriculture waste of Citrullus Lanatus peels in refrigerant R600a on domestic refrigeration systems. Despite the findings of the COP and PDT for the R134a refrigerant fluid device, the R600a, and its nano-refrigerant versions perform superior with referring to energy consumption, cooling capability, and heat absorbed and emitted, according to the studies. The experiment presented that the nanoparticle concentration has a substantial impact on the compressor's output. The working fluid, which included 0.1% bio-based nanoparticles spread in nano-refrigerant, reduced the system's energy consumption by 71.38%. Similarly, Bi et al. [73] investigated the impact of TiO_2 on R600a and discovered that at a concentration of 0.5 g/L, the system performance boosts up by 9.5%. Bondre et al. [13] concluded that the increased COP and lower energy consumption indicate the need for a more compact and energy-efficient refrigeration system in the future.

Table 2 summarizes the performance of the domestic refrigeration system.

Table 2. Summary of performance studies in domestic refrigeration system.

Author	Refrigerant	Nanoparticle	Lubrication oil	Main points
Bi et al. [74]	R134a	TiO_2	Mineral oil	• The better performance at 0.1% mass concentration of nanoparticle with 26.1% reduction in energy usage.
Jayadi and Saidur [75]	R134a	TiO_2, Al_2O_3	Mineral oil	• The energy-saving using nanoparticles would be greater than without using nanoparticles with a 10 863 MWh reduction in energy consumed by the year 2030. • The maximum energy saving of 25% was obtained.
Ohunakin et al. [76]	LPG	TiO_2, SiO_2, Al_2O_3	Mineral oil	• Based on LPG, the nanoparticle TiO_2 and SiO_2 reduced the power consumption by 13% and 12% respectively.
Gill et al. [77]	LPG	TiO_2	Mineral oil	• The system's cooling capacity and COP grew by 18.74–32.72% and 10.15–61.49%, respectively. • Compressor energy usage and pressure ratio were reduced by 3.20–18.1 % and 2.33–8.45%.
Bondre et al.[13]	R134a	Al_2O_3	Polyol ester (POE)	• The system's COP was increased by 17.27%. • The amount of energy consumption decreased by 32.48%. • Cooling capacity was increased when nanoparticles were added to the base fluid.
Bi et al.[73]	R600a	TiO_2		• Obtained an energy saving of 9.65%, when 0.5 g/L nanoparticle was added to the refrigerant.

6. Conclusions

Nano-refrigerants have a major effect on the refrigeration mechanism. The properties, HT efficiency, and applications of nano-refrigerants are all examined in depth in this article. Nano-refrigerant research may aid the refrigeration and air conditioning industry in making a smooth alternative to sustainability. The industry has been pushed to embrace a novel kind of low-GWP refrigerants, such as HC and HFO refrigerants, as a result of growing foreign worries about refrigerants' global warming capacity. This article may be very useful in acquiring knowledge about the application and performance of nano-refrigerants during this period of transformation from high global warming potential systems to eco-friendly systems. While further research is required to understand nano-refrigerants' possible use in refrigeration systems, their impact on the thermodynamic efficiency of refrigerants and lubricants suggests that they would be widely used in the future. Based on previous research, we discovered certain benefits and merits that should be considered in future work. The utilization of nano-refrigerants enhanced the HT efficiency of VCR systems, especially in the HT of the pool and nucleate boiling.

The HT coefficient of R134a-based nano-refrigerant was enhanced by 42% and 30.2% with CuO and TiO_2 nanoparticles respectively.

The inclusion of nano-materials into the refrigerant-oil mixture has little effect on the solubility of the mixture, which aids in the oil return ratio in VCRs. The inclusion of nano-materials in the refrigerant improved the overall performance of VCRs, including cooling capacity and system coefficient of performance.

When TiO_2 was added to R134a, it obtained the highest value of COP, which was 63.5% higher than that of the Al_2O_3 nanoparticle added to R134a.

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