Nanolubricants in refrigeration systems: a state-of-the-art review and latest developments

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REVIEW

Nanolubricants in refrigeration systems: a state-of-the-art review and latest developments

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Abstract

Nanolubricants, dispersions of nanometer-scale particles in a conventional lubricant, have been one of the main subjects of recent studies aimed at increasing energy efficiency and durability of refrigeration systems. This work presents a state-of-the-art review of nanolubricants applied to refrigeration systems. Papers found in the literature were classified by the nature of the nanoparticle, namely: metals, metallic and non-metallic oxides, carbon allotropes and composites. Major mechanisms involved in the intensification of energy parameters are discussed. They are mainly related to heat transfer enhancement and to reduction of the system energy consumption. The former is due to the improvement of the thermophysical properties of the refrigerant/nanolubricant mixture, and the latter, to better tribological properties as a result of nanoparticles, acting as a lubricant additive. The experimental data collected from the literature showed a great dispersion of results, even though a tendency to improve the performance of refrigeration systems was observed. Likewise, the most challenging efforts toward the sustainable use of nanolubricants in these systems are also discussed.

Keywords Nanolubricant · Nanofluid · Nanoparticles · Refrigeration system

List of symbols

c	Nanoparticle mass fraction (%)
COP	Coefficient of performance (–)
E.E.R.	Energy efficiency ratio (BTU/h kW)
GWP	Global warming potential (–)
P	Pressure (bar)
T	Temperature (°C)

Greek symbol

ω	Lubricant mass fraction (%)

Subscripts

C	Cold
Dis	Discharge
H	Hot
Suc	Suction

Abbreviations

CNT	Carbon nanotubes
EIA	US Energy Information and Administration
IGC	Inert gas condensation
IQR	Interquartile range
GWP	Global warming potential
HVAC&R	Heating, ventilating, air conditioning and refrigerating
LPG	Liquefied petroleum gas
MO	Mineral oil
NP	Nanoparticle
NR	Not reported on literature
PAG	Polyalkylene glycol
POE	Polyol ester
PWE	Pulsating wire evaporation
SH	Evaporator outlet superheating

1 Introduction

The HVAC&R industry has been making an effort to improve the climate change performance of its products. This has been accomplished with the development of new technologies of reduced greenhouse gases emissions, through the use of low-GWP refrigerants (direct emissions) or promoting the reduction of energy consumption (indirect emissions). A

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recent report by the US Energy Information and Administration informed that global energy consumption is projected to be 50% higher by 2050 [1]. Remarkably, this increase will worsen energy scarcity and environmental pollution since, by 2050, in spite of renewable energy being expected to be the leading source of primary energy consumption [1], fossil fuels, i.e., natural gas, coal, petroleum and other liquids, will still total nearly 70% of the energy produced. According to a note published by the International Institute of Refrigeration, in 2015, the refrigeration sector, including air conditioning, consumed about 17% of all electricity produced globally [2]. Of this portion, 45% came from the residential sector, 39.6% from the industrial sector and 15.4% from the tertiary sector. These data demonstrate, unmistakably, the importance of increasing the energy efficiency of refrigeration systems to reduce global energy consumption. This can be achieved by reducing power consumption of the compressor and by enhancing heat transfer in the evaporator and condenser, thus increasing the coefficient of performance (COP). One of the many possible ways to provide these improvements has been the application of nanolubricants in the refrigeration system. Nanolubricants are fluids composed of nanoparticles with a size less than 100 nm dispersed in conventional refrigeration lubricants [3]. These solid nanoparticles can be metallic, non-metallic, ceramic, carbides, carbon allotropes, oxides, hybrid (i.e., mixtures of different types of nanoparticles) [4] or composites. The interest in adding solid particles to the lubricant relies on the fact that solids have greater thermal conductivity in relation to fluids [5]. Take, for example, diamond, which has a thermal conductivity of 2200 W/mK [6], while that of POE 32 oil (polyol ester) is 0.1472 W/mK [7]. The synthesis of nanolubricants can be done by one- or two-step methods. In the one-step method, nanoparticles are produced and dispersed, simultaneously, in the base fluid, whereas in the two-step method, they are first produced to be later dispersed in the base fluid [8]. The latter is the most used method as it is more economical and applicable to a large-scale operation. On the other hand, the resulting nanofluid does not have good stability as the one-step method [9]. Nanoparticles can be produced by IGC (inert-gas condensation), chemical precipitation, thermal projection, chemical vapor deposition and spray pyrolysis [10]. The most prominent one-step method is PWE (pulsating wire evaporation), while the two-step method includes the production of nanoparticles by chemical, physical or mechanical processes and their dispersion in high-shear mixing equipment or ultrasonic vibrators [11].

One of the reasons for opting for the nanometric scale is the fact that, compared with the micrometric scale, nanoparticles would reduce the formation of clusters and avoid the obstruction of small passages [12]. Indeed, Kumar and Elansezhian [13], Padmanabhan and Palanisamy [14] and Wang et al. [15] found no damage or obstruction to refrigeration systems analyzed with nanolubricants. Sharif et al. [16] used a silica nanolubricant in an automotive air conditioning system and, after making a cross sectional cut in the micro-channel evaporator, showed no evidence of fouling or erosion. Additionally, the nanoscale nature of the resulting fluid provides the formation of nanolayers at the solid–liquid interface, between the nanoparticle and the base fluid. They are formed by liquid molecules close to the surface of the nanoparticle, acting as a thermal bridge, which increases the thermal conductivity of the nanofluid [17]. Another mechanism that contributes to increase the heat transfer at nanoscale is the Brownian motion, which is the random movement of particles suspended in a fluid, generated by their collision with fast-moving fluid molecules. This pattern describes a fluid in thermal equilibrium, in which there is no preferential direction of the particles [18], but rather a random movement, due to the kinetic energy of the fluid. At a finite temperature, electrons and ions in any matter undergo constant thermal agitation, emitting thermally excited electromagnetic waves in two ways: (i) the propagating modes that leave the surface of the emitter and radiate freely into space, and (ii) the non-propagating ones, which do not transport energy across the surface, in normal direction, unless a second surface is brought into the first encapsulation of phonons, characterizing near-field radiation [19]. With the Brownian movement, random collisions cause heat to be transported by phonons between nearby particles, which increases thermal conductivity [20].

In refrigeration systems, lubricant oil (or nanolubricant), whose function is to lubricate moving metal parts, is introduced directly into the compressor crankcase. The lubricant reduces the power loss due to friction, in addition to preventing internal gas leaks, absorbing thermal energy from cylinder components and protecting it from corrosion and oxidation [21]. The high boiling point of a typical lubricating oil prevents it from vaporizing at any part of the vapor compression cycle. The nanolubricant circulates through the components of the cycle and returns to the compressor. Even at the compressor discharge flow, the hottest point of the cycle, superheated vapor and a mist of oil coexist at lubricating oil to refrigerant mass ratios that can amount to 10%. Oil distribution along the cycle determines how the system is affected, favorably or not, by the thermal energy exchange processes that take place in the condenser and evaporator. As for tribology, the nanometric scale makes it easier to insert nanoparticles in the surface roughness, compensating for the loss of mass due to wear [22]. Authors such as Bi et al. [23], Alawi et al. [24] and Sharif et al. [5] point out that nanoparticles can increase the solubility between refrigerant and lubricant. Zou et al. [25] revealed an increase in solubility between an HFC refrigerant (R134a) and mineral oil (MO) with the use of TiO_2 nanoparticles. Bi et al. [26] observed an increase in the oil return rate with the addition of TiO_2

and Al_2O_3 nanoparticles in POE oil with R134a. Górny et al. [27] affirmed that over 70% of damaged compressor parts are a consequence of the lubricant/refrigerant mixture action. The main reasons for failures are lack of oil (defective installation, poor miscibility, refrigerant leaks etc.), improper oil, formation of mixture of liquid agent with oil, and liquid impact. On the other hand, when it comes to nanolubricants, increase in the cooling capacity, reduction on energy consumption, and an improvement of system tribological conditions have been reported by several authors [28–31]. The fact has raised the attention of researchers to become a potential alternative to improve the energy efficiency of refrigeration systems and components. Figure 1 depicts the number of publications over the years on nanolubricants, confirming the great interest of the scientific community.

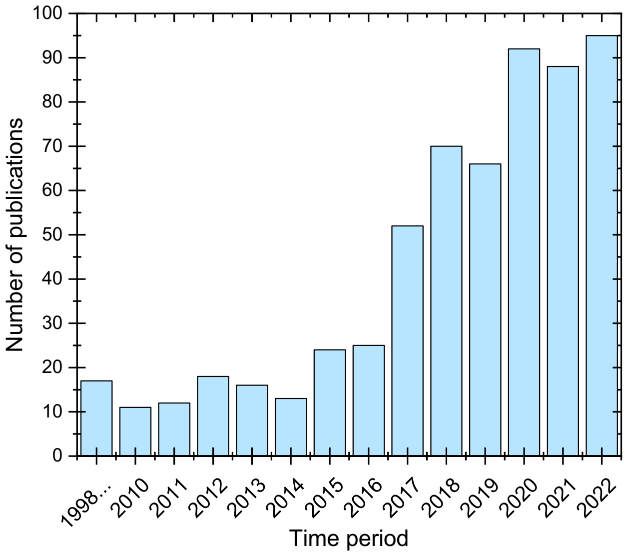

Fig. 1 Number of publications on nanolubricants over the years (keyword: nanolubricant; database: www.sciencedirect.com)

A number of reviews on nanolubricants for refrigeration systems can be found in the literature [32, 33]. The review papers on nanorefrigerants and nanolubricants are shown in Table 1, and it is possible to observe the present review is the only one dedicated to refrigeration nanolubricant only. From this initial review, it becomes clear that the application of nanoparticles to the lubricating oil, in general, presents better performance for both the compressor and the vapor compression cycle. It is also observed that distinct approaches were adopted in these reviews. Alawi et al. [32], for instance, organized the literature based on the material of the nanoparticle, which included: Al_2O_3, CuO, TiO_2, CNT, Cu and others. From an early survey, Azmi et al. [34] commented their main attribute, namely, a positive impact on compressor performance due to tribological improvement. In a comprehensive review of nanofluids applied to refrigeration systems, Bhattad et al. [35] mentioned some works on nanolubricants, from which the introduction of nanoparticles to the lubricating oil resulted in percentage reductions in compressor energy consumption ranging from 11.8 to 13.3%. The research conducted by Sharif et al. [5] concentrated on reviewing the mechanisms that result in improved performance of vapor compression refrigeration systems. Yang et al. [36] in their review evaluated the applicability of nanofluids to a number of refrigeration systems that include HVAC units, industrial and domestic refrigerators, heat pumps and heat pipes. An overview of previous review investigations was presented, and surveyed literature was aggregated to show the application of nanomaterial technology in refrigeration systems. Publications were classified by each nanomaterial and research gaps were identified and discussed. Recently, review papers have been principally focused on stability, thermophysical properties of nanofluids, impacts on refrigeration systems [37], boiling, condensation and tribological properties [38].

The purpose of this paper is threefold: (i) to carry out an update on the state of the art regarding the experimental

Table 1 Review papers on nanorefrigerants and nanolubricants

Authors	Year of publication	Subject covered	Number of references cited
Alawi et al. [32]	2015	Nanorefrigerant/nanolubricant	42
Redhwan et al. [120]	2016	Nanorefrigerant/nanolubricant	45
Azmi et al. [34]	2017	Nanorefrigerant/nanolubricant	134
Bhattad et al. [35]	2018	Nanorefrigerant/nanolubricant	143
Sharif et al. [5]	2018	Nanorefrigerant/nanolubricant	67
Yang et al. [36]	2020	Nanorefrigerant/nanolubricant	100
Senthilkumar et al. [33]	2020	Nanorefrigerant/nanolubricant	31
Bharathwaj R et al. [38]	2021	Nanorefrigerant/nanolubricant	107
Yildiz et al. [37]	2021	Nanorefrigerant/nanolubricant	161
Present work	2021	Nanolubricant	127

application of nanolubricants in vapor compression refrigeration systems; (ii) to classify nanolubricants by particles type and by material, and (iii) to analyze nanolubricants by their effects on performance parameters of refrigeration systems for each type of nanoparticle, classifying it by its nature (oxides, metals, composites and allotropic forms of carbon). The objective is to highlight the nature of the nanoparticles that make up the nanolubricant, from the most investigated ones to those that still require more experimental data. Also, this work intends to go further than a simple of published papers by identifying the main challenges to be faced by those involved with nanolubricants, before large-scale application is achieved. An attempt is made in reaching common recommendations for better conclusions in the future. Furthermore, this review was restricted to nanolubricants and their effect upon thermal performance of refrigeration systems. Those papers related exclusively to the synthesis, stability, and thermophysical properties of nanolubricants were not included, since there are updated and high-quality review papers in the available literature that have focused on these topics [39–43].

2 Application of nanolubricants in refrigeration systems

To facilitate the presentation of the works found in the literature involving the application of nanolubricants in refrigeration systems, they were classified according to the nature of the nanoparticle used to produce the nanolubricant, namely metals, metal oxides, allotropes of carbon and composites, as summarized by Tables 2, 3, 4 and 5.

2.1 Metallic nanoparticles

Currently, the literature related to the application of metallic nanoparticles to refrigeration systems is scarce. Ajayi et al. [44] used a nanolubricant composed of 0.04% nickel mass fraction in MO synthesized by the one-step process and applied to a system with R134a refrigerant. A hybrid energy source refrigerator was used for the experiment, which consisted of three stages, depending on the energy sources used: (a) only the electricity network; (b) battery only and (c) hybrid battery/solar energy source. The interest in the use of alternative energy sources stems from the possibility of implementing this system for the preservation of vaccines in remote locations with no access to the electricity network, as well as in domestic and commercial applications. The lowest pull-down temperature was achieved with the hybrid energy source and nanolubricants. The use of nanolubricants, however, increased energy consumption in all cases, with the largest increase obtained with the battery-only mode, 28.9%. The authors stated that further investigation is required to understand the increase in energy consumption of the refrigeration system caused by the use of nanolubricants.

More recently, Yilmaz [45] studied the performance of (CuO/Ag)/POE nanolubricants in a conventional refrigeration system operating with R134a. The methodology used by the author to measure the effect of adding CuO/Ag alloy nanoparticles (0.5%vol) on the performance of the refrigeration system was the transient pull-down test method. The results showed that, with the addition of the nanoparticles, the system operated with lower suction and discharge pressures, on average 15.4% and 14%, respectively, while COP and the heat transfer rate were intensified by 20.88% and 16%, respectively; finally, power consumption was reduced by 3.9% when compared to the system operating with pure POE lubricant.

2.2 Metallic and non-metallic oxides

Among the studies of nanolubricants in refrigeration systems, the application of metal oxide nanoparticles is the most numerous group. One reason is because oxide nanoparticles are less expensive and the refrigerant-oil solubility can be increased with the addition of these nanoparticles,

Table 2 Summary table of studies that used nanolubricants containing metallic nanoparticles

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Ajayi et al. [44]	Ni	MO/R134a	One-step/not used	0.04%w	Hermetic reciprocating/NR	COP: increment of 12.8%; Energy consumption: increment of 17.4%
Yilmaz [45]	(CuO/Ag)	POE/R134a	Sonication/not used	0.5%vol	Hermetic reciprocating/0.18 kW	COP: increment of approximately 21%; Cooling capacity: enhancement of 16%; Energy consumption: reduction of 4%

Table 3 Summary table of studies that used nanolubricants containing metallic and non-metallic oxide nanoparticles

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Fu et al. [48]	Fe_3O_4	MO/(R134a/R600)	NR	NR	Hermetic reciprocating/NR	Compressor surface temperature: reduction of up to 3.5 °C; Pull-down time: reduction of 148 s
Bi et al. [27]	Al_2O_3	MO/R134a	Sonication/not used	0.06; 0.1%w	Hermetic reciprocating/NR	Energy consumption: Reduction through the use of nanoparticles: between 5 and 10%; Oil return: increase of 8% with nanoparticles
Jwo et al. [74]	Al_2O_3	MO/R134a	Sonication/not used	0–0.2%w	Hermetic reciprocating/NR	Energy consumption: Maximum reduction of 2.4% (0.1%w); COP: Maximum increase of 4.4% (0.1%w)
Kumar and Elansezhian [13]	Al_2O_3	MO/R134a	Sonication/not used	0.2%vol	Hermetic reciprocating/NR	Energy consumption: Maximum reduction of 10.32%;
Subramani and Prakash [50]	Al_2O_3	MO/R134a	Sonication/not used	0.06%w	Hermetic reciprocating/NR	COP: Increase of 33% and 11.2% (in relation to pure POE and MO, respectively); Subcooling: increment of 8.3 °C (relative to the pure POE oil)
Subramani et al. [51]	Al_2O_3	MO/R134a	Sonication/not used	0.1 g/l	Hermetic reciprocating/NR	Cooling time: reduction of up to 20 min; COP: increment of 20%
Kumar et al. [52]	Al_2O_3	MO/R600a	Sonication/not used	0.06%w	Hermetic reciprocating/NR	COP: increment of 19.6%; Energy consumption: reduction of 6% with MO compared to pure POE; increase of 11.5% with the addition of nanoparticles and MO; Cooling time: reduction of 29% compared to pure POE Subcooling: 3 °C using the nanolubricants, without subcooling was not observed

Table 3 (continued)

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Almeida [75]	Al_2O_3	MO/R600a	Sonication/not used	0.1 and 0.5 g/l	Hermetic reciprocating/NR	Energy consumption: Reduction of 22% (0.1 g/l) and 25.9% (0.5 g/l) with nanoparticles in MO compared to POE. Approximately, reduction of 5% by the addition of nanoparticles
Yusof et al. [53]	Al_2O_3	POE/R134a	Sonication/not used	0.02%vol	Hermetic reciprocating/0.15 kW	Energy consumption: the highest reduction of 2.1%; COP: increment of 5.9% compared to the system operating with the pure POE oil
Gill et al. [29]	Al_2O_3	MO/LPG POE/R134a	Sonication/not used	0.2 g/l	Hermetic reciprocating/0.100 kW	Energy consumption: Increase of 0.5% (in relation to pure MO/LPG) and reduction of 2.7% (in comparison to POE/R134a) COP: Reduction of 16.45% (in relation to pure MO/LPG) and increase of 28.6% (in comparison with POE/R134a)
Soliman et al. [54]	Al_2O_3	MO/R134a POE/R134a	Sonication/not used	0–0.15%w	Hermetic reciprocating/0.160 kW	Energy consumption: reduction of 9.3% for MO and 13.7% for POE by the use of nanolubricants, related to their respective base oil; COP: increment of 8.7% for MO and 11% for POE by the use of nanolubricants, related to their respective base oil
Shareef et al. [55]	Al_2O_3	MO/R22	Sonication/not used	0–0.2%w	NR/NR	Discharge temperature: maximum reduction of 20 °C (0.15%w); COP: maximum increment of 25.6% (0.05%w)
Bondre et al. [29]	Al_2O_3	POE/R134a	Sonication/not used	0–0.2%w	NR/0.16 kW	COP: maximum enhancement of 17.2% (0.1%w/MO); Increment on the cooling capacity of the system; Energy consumption: maximum reduction of 34.48%

Table 3 (continued)

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Nair et al. [57]	Al_2O_3	PAG/R134a	Sonication/not used	0.5%w	Semi-hermetic reciprocating/3.0 kW	COP: maximum increment of 6.5%; Energy consumption was not altered by the addition of nanoparticles; With the addition of nanoparticles the subcooling incremented
Prasad and Kumar [58]	CuO	PAG/R134a	NR/NR	0–0.025%vol	Hermetic reciprocating/NR	COP: increment of 41.5% using four pairs of magnets, without using nanolubricants. Adding the nanoparticles, the maximum increment observed was 32% (0.025%vol). Using both, nanoparticles (0.025%vol) and magnets, the maximum increment was 25.14%
Kumar et al. [59]	CuO	MO/GLP	Sonication/not used	0–1.0%w	Hermetic reciprocating/NR	Reduction of the operating pressures of the system; Discharge temperature: maximum reduction of 10 °C (1.0%w); Energy consumption: 7.3%; COP: maximum increment of 46%
Anish et al. [60]	CuO	PAG/R22	Magnetic stirrer/not used	0.05%vol	Hermetic reciprocating/NR	COP: maximum increment of 23.5%;
Bandgar et al. [61]	SiO_2	MO/R134a POE/R134a	Sonication/not used	0–1.5%w	Hermetic reciprocating/NR	Cooling time: maximum reduction of 28.16% (0.5%w SiO_2/MO); Work of the compressor: maximum reduction of 13.89% (0.5%w of SiO_2/MO); COP: maximum increment of 4.39% (for 0.5%w of SiO_2/MO)

Table 3 (continued)

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Sharif et al. [16]	SiO_2	PAG/R134a	Sonication/not used	0–0.7%vol	Automotive piston type/NR	Work of the compressor: significant reduction was found from the 0.05%vol of nanoparticles; COP: maximum increment of 24% (0.5%vol); There was no sedimentation, erosion or clogging of the evaporator microchannels caused by the nanoparticles
Gill et al. [29]	SiO_2	MO/GLP MO/R134a	Sonication/not used	0.2 g/l	Hermetic reciprocating/0.100 kW	Compressor consumption: 12.67% lower compared to pure MO and 13.29% lower compared to Al_2O_3/MO; Cooling capacity: increment of 13.07%; COP: increment of 31.05%
Ohunakin et al. [62]	SiO_2	MO/GLP	Sonication/not used	0–0.6 g/l	Hermetic reciprocating/0.89 kW	Cooling capacity: maximum increment of 7.47% and minimum reduction of 29.91%, depending on the refrigerant charge and nanoparticle volume concentration; Energy consumption: maximum reduction of 8.57%; COP: maximum increment of 18.83%
Wang et al. [15]	$NiFe_2O_4$	MO/R410a	Sonication/Tricresyl phosphate (TCP)	2.5 g/l	Hermetic rotary/11.5 Btu/h (3.47 kW)	Increment on the E.E.R.; Satisfactory miscibility between the MO and HFC refrigerant for ensuring the system operation
Bi et al. [27]	TiO_2	MO/R134a	Sonication/not used	0.06 and 0.1%w	Hermetic reciprocating/NR	Energy consumption: reduction of 11.3% (0.1%w); Increment on the returning oil to the compressor

Table 3 (continued)

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Bi et al. [24]	TiO_2	MO/R600a	Sonication/not used	0–0.5 g/l	Hermetic reciprocating/NR	Lower temperatures were found inside the refrigerated compartment Reduction of the evaporation temperature with the increment on the nanoparticle concentration; Energy consumption: reduction of 9.6% (0.5 g/l)
Padmanabhan and Palanisamy [14]	TiO_2	MO/R134a MO/R436A MO/R436B	Magnetic stirrer/not used	0.1 g/l	Hermetic reciprocating/NR	Maximum reduction of 26% on the work done by the compressor; COP: maximum increment of 34.76%, relative to the system operating with pure POE oil
Sabareesh et al. [32]	TiO_2	MO/R12	Magnetic stirrer/not used	0.01%vol	Hermetic reciprocating/0.5 TR (1.76 kW)	COP: maximum increment of 17%; Compression work: maximum reduction of 11%
Sajumon et al. [63]	TiO_2	MO/NR	Magnetic stirrer/not used	0.02%vol	Hermetic reciprocating/NR	Energy consumption: reduction of 9.3%; COP: increment of 17%
Fedele et al. [64]	TiO_2	POE/R134a MO/R134a	Sonication/not used	0–0.5%w	Hermetic rotary/NR	All the effects of using nanolubricants relayed between the estimated uncertainty region
Babu et al. [66]	TiO_2	MO/R134a	Sonication/not used	0.1; 0.2 g/l	Hermetic reciprocating/NR	Higher cooling velocity; COP: increment of 20.2%; Cooling capacity: increment of 10.3%; Energy consumption: reduction of 9.65%
Sutandi et al. [67]	TiO_2	POE/R22	Magnetic stirrer/not used	0–0.6 g/l	NR/2.5 kW	Only the 0.2 g/l concentration presented enhancements; Energy consumption: reduction of 6.3%; Cooling capacity: increment of 6.5%; COP: increment of 12.2%

Table 3 (continued)

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Razzaq and Ahmed [69]	TiO_2	MO/(R22/HC)	Magnetic stirrer/not used	0.1–0.4%vol	Hermetic rotary/3.40 kW	COP: maximum increment of 18.5% at the highest concentration; Energy consumption: maximum reduction of 5.2% at the same volume concentration of the highest COP
Kumar and Elansezhian [70]	ZnO	PAG/R152a	Sonication/not used	0–0.5%vol	Hermetic reciprocating/NR	Energy consumption: reduction of 21% (0.5%vol);
Kumar and Singh [30]	ZnO	MO/(R290/R600a)	Sonication/not used	0.2–1.0%w	Hermetic reciprocating/NR	Energy consumption: reduction of 7.48%; COP: increment of 46%
Saravanan and Vijayan [72]	Al2O3/TiO2	POE/R134a	Magnetic stirrer/not used	0.1 g/l	Hermetic reciprocating/NR	Energy consumption: reduction of 12.3% (0.1 g/l) COP: increment of 11.9%; Slight reduction on the compressor discharge temperature
Chauhan [73]	Al_2O_3/SiO_2	PAG/R134a	Magnetic stirrer and Sonication/not used	0.02–0.1%vol	Hermetic reciprocating/1.75 kW	Optimal concentration of 0.08%; Cooling capacity: maximum increment of 12.7%; Energy consumption: maximum reduction of 21%; COP: maximum increment of 42%

Table 4 Summary table of studies that used carbon allotropes

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Abbas et al. [80]	CNT	MO/R134a	Sonication/Not used	0.01–0.1%w	NR/NR	COP: increment of 4.2%
Xing et al. [81]	Fullerene C_{60}	MO/R600a	Sonication/Span-40 and tween-60	3 g/l	Hermetic reciprocating/0.125 kW	Energy consumption: reduction of 4.5%; COP: increment of 5.3%
Kamaraj and Babu [82]	Amorphous Carbon	POE/R134a	Magnetic stirrer/not used	0.2 g/l	Hermetic reciprocating/NR	COP: increment of 9.0%; Energy consumption: reduction of 15.3%
Moroz et al. [83]	Fullerene C_{60}	MO/R600a	Sonication/Tween-80	0.5%w	Hermetic reciprocating/0.12 kW	Average reduction of 4% on the energy consumption; The nanoparticles did not affect the cooling capacity
Fedele et al. [62]	Carbon nanohorns	POE/R134a	Sonication/not used	0.1%w	Hermetic rotary/NR	All the effects of using nanolubricants relayed between the estimated uncertainty region
Lou et al. [84]	Graphite	MO/R600a	Sonication/not used	0.05–0.5%w	Hermetic reciprocating/NR	Reduction on the energy consumption of 4.5%; Reduction on the cooling time in 15.2%
Marcucci Pico et al. [30]	Diamond	POE/R410A	Sonication/oleic acid	0.1% and 0.5%w	Hermetic scroll/15 kW	Increment of 7% on the cooling capacity for the highest mass fraction; Increment of 8% on the COP The energy consumption remained at the same level
Marcucci Pico et al. [85]	Diamond	POE/R32	Sonication/oleic acid	0.1% and 0.5%w	Hermetic scroll/15 kW	Increment of 2.4% on the cooling capacity for the highest mass fraction; Increment of 3.2% on the COP The energy consumption remained at the same level

Table 4 (continued)

Author	NP	Lubricant/refrigerant	Synthesis/surfactant	NP concentration (%)	Compressor type/nominal capacity	Results
Yang et al. [86]	Graphene nanosheets	POE/R600a	Sonication/not used	10–30 mg/l	Hermetic reciprocating/NR	Increase of 5.6% on the cooling velocity; Maximum reduction of 20.3% on the energy consumption; Reduction of approximately 10 °C on the shell compressor temperature;
Babarinde et al. [87]	Graphene	MO/R600a	Sonication/not used	0.2, 0.4 and 0.6 g/l	NR/NR	COP: maximum increment of 50% (0.4 g/l); Energy consumption: reduction of 20% (0.4 g/l); The addition of nanoparticles decreases the discharge pressure of the compressor
Jong Choi et al. [88]	MWCNT	POE/R134a	Sonication/Triton X-100	0.05–0.1%vol	Hermetic reciprocating/NR	Increase in suction pressure; Decrease in the dissolved refrigerant in the POE-based nanolubricant with the increment in concentration of MWCNT

Table 5 Summary table of studies that used composite nanoparticles

Author	NP	Lubricant/refrigerant	Synthesis	NP concentration (%)	Compressor type/nominal Capacity	Results
Jia et al. [91]	(1) MoFe2O4/NiFe2O4 (2) MoFe2O4/NiFe2O4/fullerene	MO/R134a	Sand mill/Span 80	1.615%vol 0.8075%vol	Hermetic reciprocating compressor/0.120 kW	The cooling capacity remained approximately constant with the use of nanolubricants. Maximum increments in COP were 1.01% and 5.33% for the nanolubricants (1) and (2), respectively
Wang et al. [92]	Fullerene(C70)/NiFe2O4	MO/R22	Sand mill/span 80	2 g/l	Hermetic rotary/3.2 kW	Maximum reduction of 0.6% in the compressor power consumption Maximum increment of 1.23% in COP

as noted by Zou et al. [25], Bi et al. [26] and Wang et al. [15]. Among the types of oxide nanoparticles used, one has alumina (Al_2O_3), titanium dioxide (TiO_2), silica (SiO_2), copper oxide (CuO), zinc oxide (ZnO), magnetite (Fe_3O_4) and nickel ferrite ($NiFe_2O_4$). Figure 2 illustrates the number of studies found in the literature regarding the application of nanolubricants composed of oxide nanoparticles in refrigeration systems. A description of the works follows. It is observed that most of them were carried out with Al_2O_3 and TiO_2.

Fu et al. [46] reported an increase in the performance of a domestic refrigerator, operated with refrigerant mixture HFC134a/HC600a, by adding Fe_3O_4 nanoparticles to the MO lubricant. The authors observed reductions of 2.2 and 3.5 °C on the surface of the compressor shell and discharge temperature, respectively. Besides, they reported a slight reduction in power consumption and a reduction of 148 s in the pull-down time when using the nanolubricant.

Bi et al. [26] investigated the application of Al_2O_3 nanoparticles in MO as a replacement for POE oil in a system with R134a refrigerant. The mass fractions of the nanoparticles used for the experiment were 0.06% and 0.1%. The greatest reduction in energy consumption with this particle added to MO was 23.24% with 0.06%w. Assuming that the improvement in energy savings could be attributed to the difference between the lubricants used, the authors found that pure MO, compared to POE, resulted in 16.67% higher energy savings. According to the authors, the gain with MO oil was the most relevant, and the estimated gain with the use of nanoparticles varied between 5 and 10%. Furthermore, the rate of oil return to the compressor, operating with MO, increased by 8% with the addition of nanoparticles, due to the increased oil-refrigerant solubility.

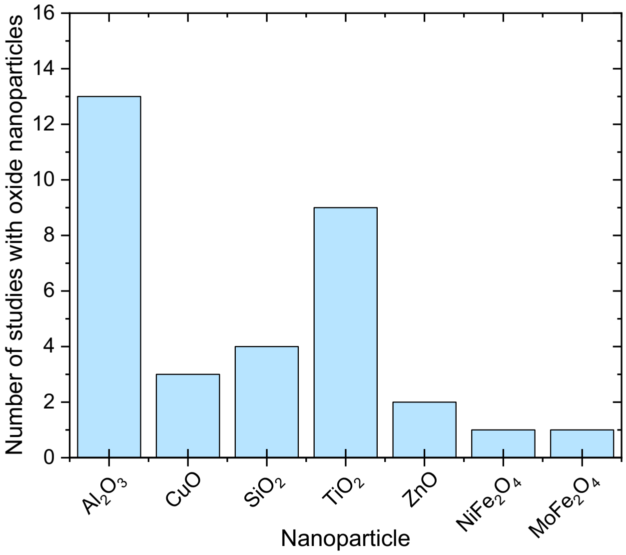

Fig. 2 Number of studies found in the literature regarding the use of oxide nanoparticles in refrigeration systems

Jwo et al. [47] included Al_2O_3 nanoparticles with mass fractions of 0.05%w, 0.1%w and 0.2%w, in a R134a system. They achieved a maximum reduction in compressor energy consumption of 2.4% and a maximum gain in COP of 4.4%, obtained with the mass fraction of 0.1%w. Kumar and Elansezhain [13] applied a nanolubricant with a 0.2% volumetric concentration of Al_2O_3 in PAG oil in a R134a system. They found a 10.32% reduction in energy consumption and an increase in COP with an increase in the capillary tube until a value of 3.5 was reached with the tube length of 10.5 m. Subramani and Prakash [48] investigated the application of a MO nanolubricant with 0.06% Al_2O_3 mass fraction in a R134a vapor compression refrigeration. An increase of 53% in the heat transfer coefficient was observed, with the nanolubricant. Also, the time for reducing the temperature of the cooling load decreased by 27%. At the condenser outlet, the subcooling obtained with the nanolubricant was 8.3 °C, while with the pure POE oil there was no subcooling. Regarding energy consumption, reductions of 18% and 25% occurred when using pure MO and nanolubricant, respectively, in relation to pure POE. Thus, the COP with the use of nanolubricant is 33% and 11.2% higher compared to pure POE and MO, respectively. Subramani et al. [49] carried out a comparative study of the use of Al_2O_3, CuO and TiO_2 nanoparticles as a lubricant additive for refrigeration systems with R134a/MO at a concentration of 0.1 g/l. Reductions of 10, 15 and 20 min were found in the pull-down time for nanolubricants containing nanoparticles of Al_2O_3, CuO and TiO_2, respectively. The energy consumption showed the same behavior, yielding percentage reductions of 4.3%, 12% and 15.5% for nanoparticles of Al_2O_3, CuO and TiO_2, respectively. Following the same order, the COP presented increments of 11.5%, 16.13% and 20%, in relation to the system operating with pure MO (SUNISO 32VG). Moreover, it was reported that, when using nanolubricants, the refrigerant condenser outlet temperature was reduced by 5, 6 and 8 °C for the Al_2O_3, CuO and TiO_2 nanoparticles, respectively. Kumar et al. [50] investigated the heat transfer enhancement in a R600a domestic refrigerator with nanolubricant composed of Al_2O_3 and MO. The nanolubricant was produced by the two-step method, in which 0.06% of Al_2O_3 mass fraction was added to MO. For dispersion, ultrasonication was applied for a period of 24 h, by means of which a 3-day period with no decanting nanoparticles was achieved. For a temperature reduction from 28 to 1 °C of the refrigerated compartment, the pull-down time decreased by 29% with the nanolubricant in relation to pure POE. Also, the system showed a subcooling of 3 °C, when using the nanolubricant, in opposition of no subcooling for pure POE. Furthermore, the reduction in power consumption when using MO instead of pure POE was 6%, and this value increases to 11.5% when introducing nanoparticles to MO, compared with the pure POE oil. Finally, the COP presented an increase of 19.6% when replacing pure POE with nanolubricant and 5.41% between this and pure MO. Almeida (2015) [78] evaluated the performance of a beverage refrigerator operating with MO-Al_2O_3 nanolubricant (0.1 and 0.5 g of Al_2O_3/L of lubricant) and refrigerants R600a or R134a. Comparisons between pure MO/R600a and pure POE/R134a were performed. The addition of nanoparticles, 0.1 g/l and 0.5 g/l, reduced energy consumption by 22% and 25.9%, respectively, in relation to the pure POE/R134a cycle. The addition of nanoparticles, without changing the refrigerant, caused an estimated 5% reduction in energy consumption. The performance of a mini-bar type domestic refrigerator with the application of a nanolubricant composed of POE oil and Al_2O_3 was also investigated by Yusof et al. [51]. For the nanoparticle concentration of 0.2%vol and at different refrigerant charges, the greatest reduction in energy consumption was 2.1%, while the greatest enhancement of COP was 2.67, which is 3.9% higher in comparison with the COP obtained by the system operating with pure lubricant. The largest COP increase was obtained with a refrigerant load equivalent to an evaporating pressure of 2.48 bar, with 2.15, or 5.9%. Gill et al. [28] analyzed the performance of a mini-bar type refrigerator using the refrigerants R134a and LPG (liquefied petroleum gas) with lubricants POE, MO and MO-Al_2O_3 nanolubricant, at a concentration of 0.2 g/l. In relation to the compressor power consumption, the nanolubricant, when compared to pure MO/LPG and POE/R134a, showed an increase of 0.5% and a decrease of 2.7%, respectively. The system COP, when operating with the nanolubricant, was reduced by 16.45%, compared to pure MO/LPG and increased by 28.6% for POE/R134a.

Soliman et al. [52] evaluated the performance of a R134a refrigeration system operating with Al_2O_3/MO and Al_2O_3/POE nanolubricants. The evaluation of the Al_2O_3/MO system revealed the existence of an optimal mass fraction of nanoparticles (0.1%w), with a 9.3% reduction in energy consumption (kWh) and a COP increase of 8.7%. With Al_2O_3/POE nanolubricant, the system performance was increased of 11% and 13.7%, respectively. In a recent study [53], Al_2O_3/MO (MO-4E) nanolubricants containing different concentrations of nanoparticles were used in a window-type R22 air conditioner. The compressor discharge temperature was found to decrease with mass fraction of nanoparticles increases, by as much as 20 °C for 0.15%w. In terms of COP and specific compressor consumption, an optimum mass fraction of 0.05%w was found, showing an increase of up to 25.6% in COP. Bondre et al. [54] added Al_2O_3 nanoparticles to POE oil at mass fractions of 0.05%, 0.1% and 0.2% in a R134a refrigeration system. Preparation of the nanolubricant followed the two-step method, while for the dispersion a sonicator type probe and a magnetic stirrer were used for a period of 4 h. This procedure maintained the stability of the nanolubricant without sedimentation for a period of 11 days. The best results were obtained for a mass fraction of 0.1%w, with which the largest increase in COP was 17.2%. The cooling capacity increased with the nanolubricant and the maximum reduction in energy consumption was 34.48%. Recently, Nair et al. [55] evaluated the performance of Al_2O_3/PAG nanolubricants in a semi-hermetic reciprocating compressor operating with R134a at 0.5%w mass fraction. The dispersion of the nanoparticles in the PAG lubricant led to a maximum increase of 6.5% on the COP of the system. On the other hand, the energy consumption remained at the same level with the use of nanolubricant. The subcooling at the compressor outlet was increased by up to 4 K with the addition of the nanoparticles. According to the authors, the increase in subcooling at the condenser outlet could be caused by two possible reasons: (i) higher heat transfer coefficient in the boundary layer due to the presence of nanoparticles, and (ii) lower specific heat of refrigerant/nanolubricant mixture which means higher temperature drop for the same amount of heat rejection. In this sense, the cooling capacity of the system was enhanced due to the increment in subcooling at the condenser outlet which reduces the vapor flashing during the throttling process and the quality at the evaporator inlet.

Regarding the use of copper oxide (CuO) nanoparticles in refrigeration systems, Prasad and Kumar [56] used them at volumetric concentrations of 0.01%, 0.015%, 0.02% and 0.025% in polyalkylene glycol (PAG) oil in a R134a refrigeration system. The authors applied a magnetic field to the fluid in the liquid line, between condenser and capillary tube, using 5 pairs of neodymium magnets of 11,800 Gauss of magnetic flux density each, being 13 cm the distance between each pair. The maximum efficiency of the system was obtained with 4 pairs of neodymium, and it decayed with the addition of another pair, presenting an optimal point. Without the use of nanoparticles, the maximum increase in the system COP was 41.5% for 4 pairs. With nanoparticles, however, without neodymium magnets, the system COP increase was 32.0% for the 0.025%vol volume concentration. Finally, when combining the use of nanoparticles and the application of a magnetic field, the COP increased by 25.14% at 0.025%vol. Kumar et al. [57] evaluated the effect of the mass fraction of CuO/MO nanolubricants on the suction and discharge characteristics of a hermetic compressor operating with LPG as working fluid. Compressor suction and discharge pressures were reduced with increasing nanoparticle mass fraction. Authors stated that this trend was due to nanoparticle-induced increase in the heat transfer coefficient of the LPG/nanolubricant mixture in the system heat exchangers. The discharge temperature showed a similar trend to the discharge pressure, with a maximum reduction of 10 °C for a mass fraction of 1.0%w. Authors reported that the reduction in the discharge temperature was owing to the spherical morphology and the high hardness of the nanoparticles which, in turn, improved the lubrication of the compressor. Other equally important properties were thermal conductivity and, according to Kumar et al. [57], probably, the increase in miscibility, which would facilitate the heat rejection of the compressor to the surroundings. Additionally, the findings revealed that the increase in mass fraction reduced energy consumption by up to 7.3% (for a mass fraction of 1.0%w), which was attributed to the reduction in the compression ratio and to the better tribological performance of the nanolubricant. Further, a maximum increase of 36% in refrigeration capacity and a maximum COP of 46% (1.0%w) were reported. Anish et al. [58] showed that the use of CuO/PAG (SP-10) nanolubricants increased the COP of a R22 refrigeration system by up to 23.5% at the nanoparticle concentration of 0.05%vol. The energy consumption was reduced from 559 to 480 W (~ 14%). The experimental setup used by the authors consisted of a hermetic reciprocating compressor, a fan-cooled condenser, a capillary tube, and a serpentine coil submerged in a water reservoir, as an evaporator.

Bandgar et al. [59] synthesized two nanolubricants with SiO_2 nanoparticles at mass fractions of 0.5%, 1.0% and 1.5% in MO and POE oils, and tested in a R134a refrigeration system. The experimental setup used by the authors is similar to that used by Anish et al. [58]. It was found that the pull-down time was reduced for both nanolubricants with the mass fraction of 0.5%w. The largest reductions were 26% and 8.2% at 0.5%w of SiO_2/POE and SiO_2/MO, respectively. The compressor work had a maximum reduction of 11.6% and 3.4%, also at 0.5%w of SiO_2/POE and 0.5%w SiO_2/MO, respectively. Increases in COP were 23.45% and 12.16% at 0.5%w SiO_2/POE and SiO_2/MO, respectively. The highest COP obtained was 1.14 (0.5%w SiO_2/MO). Sharif et al. [16] studied the application of SiO_2 nanoparticles, at volumetric fractions of 0.2%, 0.3%, 0.5% and 0.7% in PAG oil in an automotive air conditioner operating with R134a and revealed that the maximum increase in COP was 24% for 0.5% volume concentration. The authors cross sectioned the evaporator and found no evidence of sedimentation-induced fouling, erosion or clogging along evaporator. Gill et al. [28] also applied the SiO_2 nanoparticles, but at this time, they dispersed in MO (0.2 g/l) and tested in a domestic refrigerator operating with LPG and R134a. With the addition of nanoparticles, the power consumed by the compressor was 12.67% less than for pure MO and 13.29% less than for Al_2O_3/MO. Cooling capacity and COP were 13.07% and 31.05%, respectively, compared to pure MO. Ohunakin et al. [60] included 0.2 g/l, 0.4 g/l and 0.6 g/l of SiO_2 nanoparticles in MO and tested in a domestic refrigerator operating with LPG as alternative refrigerant for R134a. The results demonstrated that the cooling capacity had a maximum increase of 7.47% and a maximum reduction of 29.91%, depending on the refrigerant charge and the concentration of nanoparticles. The addition of SiO_2 increased compressor power consumption, with the opposite occurring for the lower refrigerant charge, in which there was a reduction of 8.57%. With the addition of nanoparticles, the largest increase in COP observed was 18.83%. The existence of an optimal refrigerant charge is common in refrigeration systems and, as observed by Ohunakin et al. [60], is repeated for systems loaded with nanolubricants.

Wang et al. [15] applied $NiFe_2O_4$ nanoparticles at a concentration of 2.5 g/l in MO in a residential air conditioning system. It was found that the energy efficiency increased with nanoparticle concentration and that the mineral-based nanolubricant—HFC refrigerant solubility was good enough to ensure a safe operation of the equipment.

Bi et al. [26] evaluated the performance of a R134a domestic refrigerator that included TiO_2 nanoparticles in MO, with mass fractions of 0.06%w and 0.1%w, to replace POE. The greatest energy savings occurred for the 0.1%w mass fraction, being 26.1% in relation to pure POE and 11.3% to pure MO. A higher oil return ratio was observed with the nanoparticles, since they, as inferred by the authors, increased the R134a-MO miscibility. Bi et al. [23] synthesized a TiO_2 nanolubricant at MO concentrations of 0.1 g/l and 0.5 g/l and introduced it into a R600a domestic refrigerator. The refrigerator compartment temperature was lower with the nanolubricants, and the evaporation temperature also decreased (with the highest concentration of nanoparticles). Additionally, the largest reduction in energy consumption was 9.6% for 0.5 g/l. Figure 3a and b shows how the use of nanolubricants affects the discharge and suction pressures of the system. Padmanabhan and Palanisamy [14] investigated the irreversibilities of a refrigeration system with refrigerants R134a, R436A and R436B with the application of MO containing 0.1 g/l of TiO_2 as a replacement for the conventionally used POE oil. The greatest reduction in compressor work and increase in COP were 26.9% and 34.76%, respectively, for R134a compared to pure POE. Sabareesh et al. [31] studied the application of TiO_2 at a volumetric concentration of 0.01%vol in MO in a R12 system. There was a 17% increase in COP compared to pure MO and a reduction in compressor work of around 11%. Sajumon et al. [61] observed an average reduction of 9.3% in energy consumption, a 5.2% increase in the refrigeration capacity and a 16% increase in the COP of a refrigeration system, with hermetic reciprocating compressor operating, with TiO_2 nanolubricant/MO, at a volumetric concentration of 0.2%vol. Fedele et al. [62] synthesized a nanolubricant for use in a R134a heat pump, with three mass fractions of 0.05%w, 0.1%w and 0.5%w of TiO_2 in POE oil and 0.1%w in MO. In opposition to the literature trend, the performance of the system with POE was better in comparison with mineral

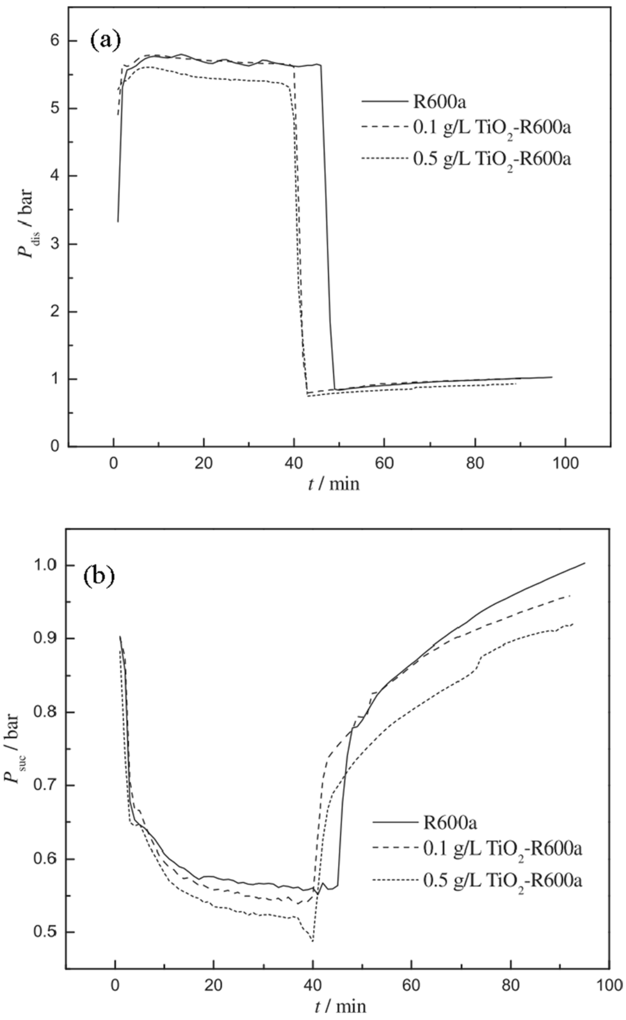

Fig. 3 Variation of compressor. **a** discharge pressure and **b** suction pressure by the addition of TiO_2 nanoparticles. *Source*: [23]

oil with or without the addition of nanoparticles. The highest COP was obtained with 0.5%w TiO_2 in POE oil, slightly higher (0.75%) in relation to pure POE and 6.41% higher in relation to MO. The authors stated that no significant gains were found, attributing the divergent results to the fact that a rotary compressor was used instead of a reciprocating one, which has been the most used in the works found in the literature. Hussen [63] synthesized a nanolubricant with 0.01%w mass fraction of TiO_2 in MO and introduced it into a R22 window-type air conditioner. The addition of nanoparticles to the system caused an increase in COP between 7.93 and 11.99% and a reduction in compressor power consumption ranging from 2.1 to 13.3%. Babu et al. [64] analyzed the use of TiO_2/MO nanolubricants in a R134a refrigeration. The system, when operating with TiO_2-nanolubricant, with a concentration of 0.2 g/l, presented the highest cooling velocity, increased the COP by 20.2%, refrigeration capacity by 10.3% and reduced energy consumption by 9.7% when compared to the system operating with pure POE lubricant. In this sense, the percentage gains reported by the author considered the combined effects of using nanoparticles, as an additive, and changing the lubricant, from POE to MO. Sutandi et al. [65] tested TiO_2/POE nanolubricants in an air conditioner (2.5 kW nominal capacity), designed for R22, operating with R290 as an alternative refrigerant. Concentrations of 0.1, 0.2, 0.4, 0.5 and 0.6 g/l were evaluated, of which only the concentration of 0.2 g/l showed improvements on system performance. Among the improvements indicated by the authors, the following stand out: (i) the reduction of 6.3% in the average power consumption, caused by the increase in the suction pressure, since the discharge pressure was kept constant; (ii) a 6.49% increase in the average refrigerating capacity, because of the increase in the thermal conductivity of the refrigerant due to the circulation of nanoparticles in the system; and, consequently, (iii) the average increase in COP of 12.2%. Gill et al. [28] also inserted TiO_2 in MO and found the greatest reduction in energy consumption of a domestic refrigerator with a nanoparticle concentration of 0.2 g/l compared to pure MO and POE, as well as Al_2O_3/MO, SiO_2/MO. In relation to pure MO, reduction in energy consumption and COP enhancement were 15% and 31.5%, respectively, with similar improvements observed for SiO_2 nanoparticles.

Recently, Jatinder et al. [66] studied the effect of using TiO_2/MO nanolubricants in a domestic refrigerator operating with R600a. The existence of an optimal concentration of nanoparticles (0.2 g/l) allowed: (i) the increase of the cooling capacity; (ii) the reduction of energy consumption and, simultaneously, (iii) the reduction of compressor discharge temperature. Thereby, the COP of the refrigerator was enhanced. In addition, through tribological tests, the authors found that this concentration resulted in a lower friction coefficient when compared to pure MO. Using a viscometer, they concluded that, besides the reduction of the friction factor, there was a further reduction in the viscosity of the nanolubricant for the optimal concentration. Thus, the authors were able to confirm that the improvements presented were due to the following causes: (i) reduction of heat generation in the operation of the compressor, by reducing the friction coefficient and viscosity that, together with the increase in thermal conductivity, allowed to dissipate more heat from the compressor, which led to the reduction of the discharge temperature and compressor work; and (ii) improvement of the transport properties, thus intensifying the heat transfer and reducing the drag of the refrigerant/nanolubricant mixture flow. Further, Razzaq and Ahamed [67] studied the effect of TiO_2/MO nanolubricants in a R22 air conditioner operating with mixture refrigerant HC/R22 (80:20 by mass) as an alternative substitute. In the study, the volume concentration of the nanolubricant ranged from 0.1 to 0.4%vol and the nanolubricants were produced by the two-step method with a magnetic stirrer. Experimental results showed that the COP increased as the volume fraction was increased, in which a maximum enhancement of 18.5% was observed at the highest volume concentration of 0.4%. Oppositely, the energy consumption was reduced with the increase in the volume concentration, reaching a minimum value of 5.2%.

Kumar and Elansezhian [68] synthesized nanolubricants, with ZnO nanoparticles at different volumetric concentrations of 0.1%vol, 0.3%vol and 0.5%vol dispersed in PAG oil. The nanolubricants were applied to R152a refrigeration system. Compressor power consumption decreased with the addition of nanoparticles. The greatest compressor power reduction and the highest COP increase were 21%, for a concentration of 0.5%vol, and 61.53% higher than the concentration of 0.1%vol, respectively. Kumar and Singh [29] used a ZnO lubricant with different mass fractions ranging from 0.2 to 1.0%w in a refrigeration system operating with R290/R600a (50:50%) mixture. With a 0.8%vol concentration, the largest reduction in energy consumption was 7.48% and the largest increase in COP was 46%.

The use of hybrid nanolubricants, nanofluids composed by the dispersion of different types of nanoparticles in lubricants, was recently addressed and, currently, there have been a few studies available in the literature [69]. One of them was presented by Saravanan and Vijayan [70] who evaluated the effect of the concentration of nanoparticles Al_2O_3/TiO_2/POE (50:50%w of nanoparticles) on the performance of a domestic refrigerator using hybrid nanolubricants. The authors found reductions of up to 12.3% in the refrigerator power with a concentration of 0.1 g/l (50:50%w). This energy reduction was a consequence of the decrease in the pressure ratio of the system operating with the hybrid nanolubricants. An increase in COP by up to 11.9% was also found, relative to the system operating with pure POE lubricant. Moreover, the authors reported slight reductions in the discharge temperature with the use of nanolubricants. Chauhan [71] studied the performance of a R134a ice plant operating with Al_2O_3–SiO_2/PAG and also isolated the effect of each nanoparticle at different volumetric concentrations, from 0.02 to 0.1%. The two-step method was used for the synthesis of the nanolubricant, first with a magnetic stirrer and later with an ultrasonic vibrator. The author noted the existence of an optimal volumetric concentration of 0.08% of the hybrid nanolubricant, in which the cooling capacity reaches the maximum increase (12.7%) and the energy consumption, its maximum reduction (21%). Consequently, the COP is maximized (42%) related to the system operating with the pure PAG lubricant oil. Another interesting behavior reported is that the optimal volume concentration found by the researcher, 0.08%vol, is the same for all tested nanolubricants, Al_2O_3, SiO_2 and Al_2O_3–SiO_2. The hybrid nanolubricant showed the highest performance improvements in the refrigeration system, followed by the SiO_2 and Al_2O_3 nanolubricants.

2.3 Carbon allotropes nanoparticles

Carbon nanoparticles can present different structures: graphite, graphene, fullerenes, carbon nanotubes (CNT), diamond, amorphous carbon, etc., and such configurations are usually called carbon allotropes [72]. Graphite has a layered structure where the carbon atoms in each layer are bonded in hexagonal arrays with covalent bonds, and the layers are bonded by secondary bonds. These secondary bonds determine weak shear strength, so they can slide by applying low forces [73]. Graphene is a single layer of graphite, which has a simple, flat, continuous sheetlike structure with a hexagonal mesh of carbon atoms [74]. Fullerenes are clusters of carbon atoms in the form of hollow structures, usually spheres. The size and geometry depend on the number of carbon atoms in it. For example, fullerene C_{60} is a highly symmetric spherical molecule composed of 60 carbon atoms positioned at the vertices of 20 hexagons and 12 pentagons [75]. CNTs have a tubular structure composed of rolled-up graphene sheets [76]. In general, carbon nanomaterials have been increasingly regarded as attractive solid lubricants for exploring efficient ways to reduce energy consumption [77]. The application of carbon nanotubes dispersed in heat transfer fluids, as reported by [78], has led to the use of rare (until now) expressions in the heat transfer literature, such as “remarkable thermal conductivity” [79].

A work with carbon nanotubes (CNT) was carried out by Abbas et al. [80] who added them in mass fractions of 0.01%, 0.05% and 0.1% in POE oil for a R134a air conditioning system. They found that the COP increased with the addition of nanoparticles and the largest increase was 4.2% for the highest mass fraction, in relation to pure oil.

Xing et al. [81] used fullerenes C_{60} at a concentration of 3 g/l in MO and applied it to a domestic refrigerator operating with R600a. Two types of reciprocating compressors were used in the study, and it was noted that the cooling capacity did not change significantly with the nanoparticles. Authors justify it by the fact that there is an oil separator in the system, which makes it difficult for the transport of nanoparticles among cycle components. In addition, for both compressors operating with the nanolubricants, power consumption decreased by 4.58% and 4.52% and the COP increased 5.6% and 5.3%. In a subsequent study [82], carbon nanoparticles were used as an additive to MO and POE lubricants to improve the performance and operability of a R134a refrigeration system. Carbon nanolubricants/POE (0.2 g/l) presented a 15.3% reduction in energy consumption, accompanied by a 9.0% increase in COP, all compared to the system operating with pure POE lubricant. Moroz et al. [83] used MO nanolubricants/fullerenes C_{60}

in a refrigeration system operating with R600a. The findings indicated an average reduction in compressor power consumption of 4% with the use of fullerenes in relation to the system operating without nanoparticles. In this sense, the authors explained that the main factor in reducing the energy consumption of the compressor was the formation of a low friction and low shear stress tribolayer among the compressor moving surfaces. They also claimed that the formation of the tribolayer was a direct consequence of the polymerization of fullerenes, caused by the operating conditions (contact pressure and temperature). On the other hand, the use of fullerene as a lubricant additive did not generate a significant increase in the cooling capacity of the system, since the reported fullerene concentration in the evaporator was relatively low. Fedele et al. [62] used single-walled carbon nanohorns with a mass fraction of 0.1%w in POE oil in a R134a heat pump. The addition of nanoparticles reduced the COP of the heat pump by 1.54% (within the 1.65% COP uncertainty range). Lou et al. [84] inserted mass fractions of 0.05%w to 0.5%w of graphite nanoparticles in MO in a R600a domestic refrigerator. The mass fraction of 0.1%w provided the greatest reduction in energy consumption (4.55%) and the greatest reduction in the pull-down time of the refrigeration system (15.22%). Above this mass fraction, increases in nanolubricant viscosity, as well as condenser and evaporator refrigerant pressures, were observed. Greater pressure drops across the heat exchangers implied a higher-pressure load and, consequently, higher compressor energy consumption. The use of diamond as a nanoparticle was carried out by Marcucci et al. [30], who tested mass fractions of 0.1%w and 0.5%w of nanoparticles in POE oil in a R410A water-to-water refrigeration system. The cooling capacity increased with the addition of diamond nanoparticles, with a maximum enhancement of approximately 7% for the mass fraction of 0.5%w. A COP increase was also observed, with the largest improvement of 8% at the same concentration. However, power consumption did not change, a fact that the authors explained as a consequence of the use of the scroll compressor, unlike most of the literature. In a recent work [85], it was found that diamond/POE nanolubricants, with a mass fraction of 0.5%w, tend to intensify the COP and the heat transfer rate of an R410A refrigeration system operating with R32 by up to 3.2% and 2.4%, respectively. The authors highlighted that these increments are within the range of estimated uncertainty. Furthermore, through tribological testing, the results showed that nanoparticles as a lubricant additive in pure POE oil reduce friction and wear for mass fractions below 0.5%w. For larger mass fractions, wear is increased significantly, exceeding the value of the wear caused by pure POE oil. Yang et al. [86] used graphene nanosheets as a lubricant additive in a R600a/POE domestic refrigerator. The study revealed that the use of graphene enhanced heat transfer, reduced energy consumption, allowed for lower temperatures of the refrigerator compartment and reduced discharge and compressor shell temperatures. According to the authors, the advantages of using this type of nanoparticle as a lubricant additive were due to a better tribological performance of nanolubricants. As a result, friction losses inside the compressor were reduced, thus lowering compressor discharge and condensation temperatures, significantly reducing the compression ratio and, consequently, compressor energy consumption. Recently, Babarinde et al. [87] also evaluated the performance of graphene nanoparticles applied to a refrigeration system operating with R600a and MO. Nanolubricants were synthesized using the two-step method by sonication and magnetic stirring for approximately 3 h and 41 min, respectively, within a temperature range of 15–20 °C. The findings exhibited a maximum enhancement of 50% in COP and a maximum reduction of 20% in the energy consumption of the refrigeration system with the nanoparticle concentration of 0.4 g/l. The authors also reported that the addition of nanoparticles to the lubricant oil decreases the discharge operating pressure, with a tendency to decrease with the increment of the nanoparticle concentration.

As the energy consumption of a refrigeration system is highly related to the suction pressure of the compressor and this pressure is also directly affected by the amount of refrigerant gas dissolved in the lubricant, Jong Choi et al. [88] studied experimentally the effect of POE/multiwalled carbon-nanotube (MWCNT) nanolubricant on the dilution process of the refrigerant. The nanolubricants used by the authors were synthesized by the two-step method adding Triton X-100 as surfactant in an ultrasonic bath at 40 kHz and 300 W during a period of 5 h. The results showed that the addition of nanoparticles can decrease the dilution of the R134a refrigerant in the lubricant and, thus, increase the suction pressure of the compressor because of the higher viscosity of nanolubricants which reduces the diffusion of the gas in the lubricant. According to a prediction model developed by the authors, the increase in the suction pressure caused by the use of nanolubricants can reduce the energy consumption of the compressor by up to 17% at the volume fraction of 0.1%vol of MWCNT.

2.4 Composite nanoparticles

Composite nanoparticles are nanomaterials with a structure constituted by two or more nanoscale components. Components with different functionalities have significant and strong mutual coupling effect, on a nanometer scale. The composite nanomaterials not only enhance significantly the intrinsic performance but also show a variety of novel features. They also break the limitations of single-component properties. These structural features can be mainly grouped into three categories: simple hybrid, core/shell structured composite nanoparticles, and multifunctional quantum dots [89]. Nanolubricants synthesized with composite nanoparticles should not be confounded with hybrid nanolubricants, which are a dispersion of more than one type of nanoparticle in a base lubricating oil [90]. There are few works in the literature that have introduced composite nanoparticles in refrigeration systems. Jia et al. [91] studied two types of nanolubricants with MO as the base fluid, namely: (1) composed of $MoFe_2O_4/NiFe_2O_4$ and (2) of $MoFe_2O_4/NiFe_2O_4/$fullerene (C_{60}–C_{70}). The volumetric fractions of nanolubricants (1) and (2) were 1.615% and 0.8075%, respectively. Two reciprocating compressors were used for the test: one for R134a and another for R600a. The maximum cooling capacity increase was 0.42% for nanofluid (2) with R600a. The authors believe that the formation of a lubricating film with nanoparticles between piston and compressor cylinder liner reduces refrigerant leaks during compression. In all cases, there was a reduction in compressor power consumption, the most relevant being 4.52% (R600a) and 0.95% (R134a) for nanolubricant (1). An increase in COP for all cases was also observed: the highest with nanolubricant (1), of 1.01% (R134a) and 5.33% (R600a). Wang et al. [92] synthesized a composite nanolubricant with fullerene C_{70} and $NiFe_2O_4$ dispersed in MO (56EP) at a concentration of 2 g/l in a R22 refrigeration cycle. The largest reduction in compressor power was 0.6% and the largest increase in COP was 1.23%.

3 Improvements caused by the type of nanoparticle

In order to highlight the principal characteristics of each type of nanoparticles, when applied to refrigeration systems. The most relevant gains found in each of the previously cited works were collected. These gains were limited to the main operating parameters of a refrigeration system in which nanoparticles tend to have an impact, such as: COP, compressor power consumption and refrigerating capacity. Data collected from the literature, maximum reductions in power consumption and maximum increments and COP, were presented graphically in the form of box plots. This type of plot was chosen as it presents simultaneously several statistical characteristics of the data set, including the mean value, median line, variability (dispersion), symmetry, and outlier values. In the box plot, the height of the box represents the interquartile range (IQR, 25–75%), the lines represent a distance equivalent to 1.5 times the IQR, and all those points outside this value are considered outliers [93].

Figure 4 shows the maximum COP increments found and classified in relation to the nature of the nanoparticle. The plot shows that there is a relevant dispersion of data for oxide nanoparticles and they also provide the highest average COP increase, between 10 and 30%, while the remainder of data is between 0 and 10%, which also holds true for carbon allotropes and composites. For the case of metallic type nanoparticles, there are only two works available in the literature, which prevents a fair comparison with other nanoparticles. Nevertheless, Fig. 4 also highlights the scarcity of experimental data related to the application of nanoparticles in refrigeration systems other than oxides, which had been extensively studied so far.

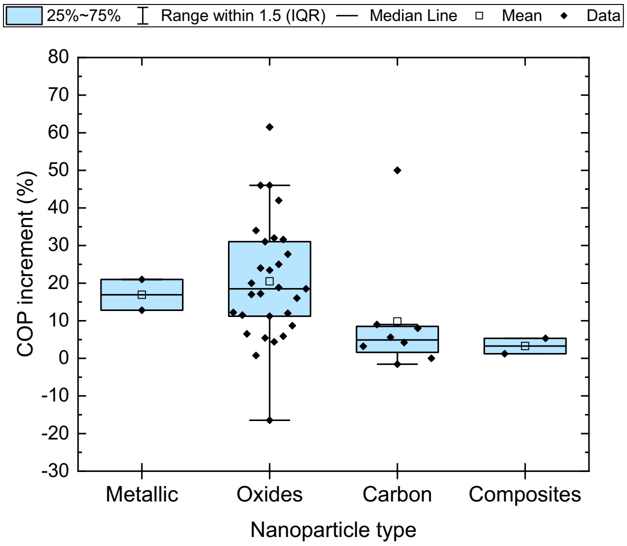

Fig. 4 Increase in COP in relation to the type of nanoparticle applied to refrigeration systems

Figure 5 depicts the reduction in compressor power consumption for each of the refrigeration systems studied here in relation to the type of nanoparticle used. Similarly, to the COP results, it can be observed that the gains with oxides are more dispersed and more likely to be predominant in comparison with other types of nanomaterials. There is also a tendency for oxides to be the nanoparticles that produce the greatest impact on the energy consumption of refrigeration systems, followed by carbon allotropes and composites. Composites and metallic nanoparticles, in some cases, may show increments in compressor energy consumption. For this case, further in-depth investigation is required, extending the range of the concentration of nanoparticles, starting from very low concentrations. This approach could be performed to find some optimal concentrations, which may lead to higher enhancements using this type of nanomaterial.

Figure 6 shows the COP gains with the reduction in energy consumption using a scatter plot, with the purpose to find out what was the main impact of each type of nanoparticle on system performance. Based on the works here discussed and from Fig. 6, it can be inferred that oxide nanoparticles tend to increase the COP by the combination of refrigeration capacity intensification and energy

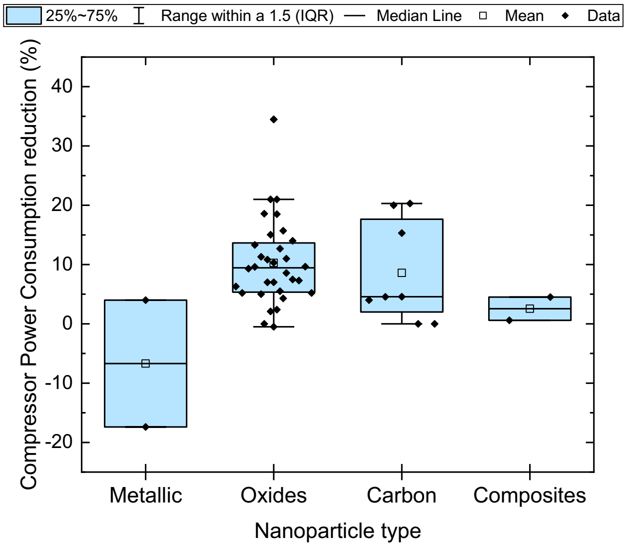

Fig. 5 Reduction in compressor power consumption in relation to the type of nanoparticle used

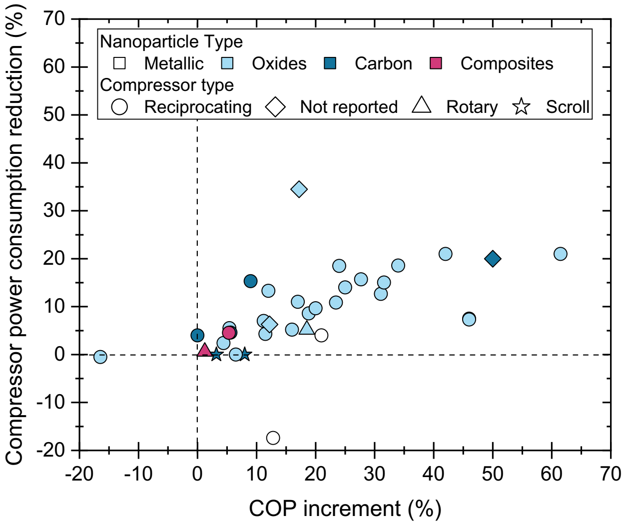

Fig. 6 Reduction in compressor power against COP increment, segregated in relation to the type of the nanoparticle

consumption reduction. As for carbon allotropes, the main impact tended to be an intensification of the heat transfer rate, while for composites, the impact was more prominent in reducing energy consumption. For the case of compound nanomaterials, during the performance evaluation, an oil separator was installed, which could have reduced the probability of finding any impact on the intensification of heat transfer enhancement [81]. In Fig. 6, the shape of the points is related to the compressor type. It is possible to observe the lack of data related to types of compressors other than the reciprocating one, (the most studied compressor so far). As can be observed, not many works have been reported with rotary or scroll-type compressors, or different types of nanoparticles. Further in-depth studies are needed so as to provide a better characterization of nanolubricant improvements in these types of compressors. Moreover, one can easily identify more often works using oxides, followed by carbon, composites and metallic, in that order. Literature on the application of composites, metallic and carbon nanomaterials is still open, regardless of the type of system, refrigerant, lubricant, or compressor. Further studies, on nanolubricants, composed of oxide nanoparticles, in refrigeration systems, with different compressors, other than reciprocating ones, would produce interesting and relevant results.

Figures 4, 5 and 6 show a great dispersion in the experimental data. This can be explained, first, by the fact that there are many other factors that influence the observed improvements, namely: system configuration (components and types), compressor, refrigerant, operating conditions, concentration of nanoparticles, the lubricating oil, the size or capacity of the application, stability, the use of surfactants, experimental methodology used, etc. To decrease this dispersion in future works, it is highly recommended to carefully control test conditions such as external air/water temperature and humidity, especially for air-cooled condensers and small charge refrigeration systems. The lack of control of these essential variables can lead to an over or underestimation of the possible improvements caused by the nanoparticles and, consequently, low repeatability. High-quality and high-precision data acquisition systems are also recommended to perform rigorous data analysis. Since several authors have reported the formation of lubricating films on friction surfaces and the deposition of nanoparticles on heat transfer surfaces could increase the performance, it is recommended to replace several components before testing a new nanolubricant in the same test rig, thus avoiding the possibility of overlapping the effects of more than one nanoparticle.

4 Main challenges and limitations of the application of nanolubricants

The main challenge currently faced by people involved with nanolubricants manufacturers (at laboratory scale) is the stability of the nanoparticle dispersion over the fluid phase. Stability is a very important factor to avoid fouling, sedimentation that can impair the transport of nanoparticles within the system. In addition, there is the possibility of clogging filter and expansion devices, and deposition in other components, which may be harmful to the operation of the system [94], in particular, the expansion valve. Furthermore, the formation of agglomerates, i.e., large clusters of nanoparticle material, can aggravate friction and wear on moving surfaces, worsening the lubrication of a system [95, 96]. In this sense, to ensure the dispersion of nanoparticles in the lubricant with the lowest possible deposition rate, methods such as ultrasonic agitation, homogenization, high-shear mixing and magnetic force agitation are used [34]. Various authors have found that, with the use of direct or indirect ultrasonication and magnetic agitation, for a certain period of time, it is possible to achieve nanolubricant stability without sedimentation for 3–20 days [54, 59, 97, 98]. To improve the stability of nanolubricants, the formation of agglomerates and collisions of nanoparticles and the consequent cohesion between them must be avoided. For this, the electrical repulsive forces of the nanoparticle surface layer must be greater than the van der Waals forces during the Brownian motion [99]. Therefore, to reach this objective, the steric stabilization method can be used, where surfactants encapsulate the nanoparticles, forming reverse micelles. Ohmae and Martin [100] present in detail the process of steric stabilization of nanolubricants, which can assist in the synthesis of stable nanolubricants for future works. Another method is electrostatic stabilization, with the development of surface charge, for example, ion adsorption or electron accumulation or depletion on the surface [99]. Stability can be assessed by sedimentation and centrifugation methods, analysis of the Zeta potential, and spectral absorbance analysis [99]. Although the stability of nanolubricants can be improved by the use of surfactants, other problems can be developed, including foaming [31] and alteration of the saturation curves of the refrigerant-oil mixture [46]. Thus, the choice of a surfactant must be a very rigorous task, so that the aforementioned problems are avoided or, at least, mitigated. Also, there should be no possibility of altering the chemical stability of the refrigerant, which should later be evaluated using the sealed glass tube method, as well as compatibility with materials conventionally used in refrigeration systems [101].

Another limiting factor in the application of nanolubricants is the degradation of the refrigerant-nanolubricant mixture, referring to the continuous decrease in the mass fraction of nanoparticles suspended in the fluid. When the refrigerant changes phase, boiling in particular, (i) some nanoparticles are deposited on the higher temperature evaporator surface due to aggregation and sedimentation, in addition to the evaporation of micro-layers. Another part of the nanoparticles remains (ii) suspended in the lubricant, staying in the liquid phase throughout the process, and the other part (iii) migrates to the vapor phase of the refrigerant by bubble capture [102]. This fraction of nanoparticles that migrates to the vapor phase does not exceed 15% yet progressing to a significant temporal degradation. Lin et al. [103] experimentally evaluated the migration rate of TiO_2 nanoparticles from the refrigerant-oil (R141b/MO) mixture to the lubricating oil during the refrigerant drying process. The authors found that, with the increase in the oil fraction and the reduction in the nanoparticle mass fraction, the migration of nanoparticles to the oil increases significantly. This is due to the formation of a layer rich in high viscosity oil, which prevents the nanoparticles from coming into direct contact with the heat transfer surface, thus allowing them to stabilize in the oil and a smaller fraction to be deposited on the heat transfer surface. Lin et al. [104] carried out a study of the degradation of refrigerant–nanolubricant (R141b/MO) mixtures during alternation processes of condensation and evaporation. The authors assessed the degradation of the nanolubricant/refrigerant mixture using the suspending ratio, defined as the ratio of the sum of the suspending nanoparticles in the nanolubricant and nanorefrigerant by the total mass of nanoparticles. This parameter was measured every condensation–evaporation alternation and compared with the initial value of the nanolubricant/refrigerant mixture. The results showed a degradation of 28–77% (i.e., the initial suspending ratio relative to the *i*th alternation suspending ratio) after 20 alternations, using TiO_2/MO (NM56)/R141b, and that degradation reduced with an increase in the mass fraction of lubricant, a reduction in the mass fraction of nanoparticles and a reduction in heating and cooling temperatures. Figure 7 shows the degradation curves of the (TiO_2/MO)/R141b nanolubricant/refrigerant mixture as a function of the number of condensation–evaporation alternation found by Lin et al. [104]. It can be seen in Fig. 7 that the oil fraction in the mixture, ω, has an important role in stability, since with the increase in the oil mass fraction the degradation process of the mixture is delayed. Lin et al. [105] found that degradation can be reduced by the pool boiling process, in which part of the deposited nanoparticles can be resuspended in the liquid and then migrate with the flow. However, these particles tend to settle when they migrate to an area of no heat transfer, where no bubbles are produced. Sharif et al. [16] conducted experiments with SiO_2 and concluded after cross sectioned the evaporator

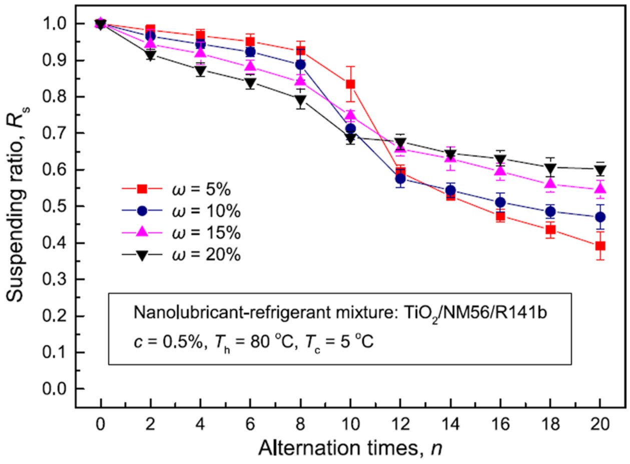

Fig. 7 Effect of the mass fraction of lubricant on the degradation of the refrigerant-nanolubricant mixture. *Source*: [104]

no evidence, visually, of possible clogging or erosion. The authors also stated that SiO_2/PAG nanolubricants does not damage the air conditioning components.

Although the sedimentation of nanoparticles is seen as one of the main challenges to be overcome before its application, some studies have found that this potential problem may be favorable for the intensification of heat transfer. Deokar and Cremaschi [106] analyzed the influence of the deposition of nanoparticles over the heating surfaces on the heat transfer and pressure drop of refrigerant/nanolubricant mixtures (R410A/POE/ZnO and R410A/POE/Al_2O_3) in single- and two-phase heat transfer. The authors reported that the heat transfer coefficient was intensified gradually over time in long-term tests due to the deposition of the nanoparticles that modified the characteristics of the heat transfer surfaces. According to the authors, these modifications increased the surface roughness and the number of bubble nucleation sites due to the presence of nanoparticles attached to the tube. As expected, owing to the increment on surface roughness, the pressure drop was increased because of the deposited nanoparticles and nanoparticle interaction at the tube wall. Figure 8 shows images of the internal surfaces of the tubes after the tests were carried out, in which it is possible to clearly observe the sedimentation and incrustation of the nanoparticles on the heat transfer surfaces.

Another challenge found in the literature regarding the use of nanolubricants is the great diversity of systems that have been used for analysis, ranging from application size (system capacity), compressor type, components, refrigerant, lubricating oil, use of surfactants, etc. Consequently, these variations prevent the experiments with nanolubricants from being easily replicated. An example of the component factor is the presence of an oil separator in the system, which can reduce the transport of nanoparticles to the components of the cycle, thus compromising the required cooling capacity gains [81]. This may cause system performance improvement to be found only with reduction in energy consumption. Further, the analysis of the viscosity gain with the addition of nanoparticles is crucial, since high viscosity values can lead to higher compressor power consumption [84], due to the increased pressure drop of the refrigerant-nanolubricant mixture and the difficulty of returning the lubricant from the system to the compressor [107].

Another measure that could help to standardize and to guarantee repeatability of experiments conducted with nanolubricants would be to work with nanoparticle concentrations in relation to the refrigerant–nanolubricant mixture and not only in relation to the lubricant. This would probably eliminate the size factor of the system, working in a normalized form. Concentrations would be measured according to the amount of refrigerant/lubricant quantity in the system. In this sense, it would be possible to find optimal concentrations regardless of the nominal capacity of the system. Also, in the literature, it is common in the literature to find undeclared charges of refrigerant or lubricating oil, turns impossible, until now, for that parameter to be characterized.

Currently, there is a large amount of published work on thermophysical properties, including thermal conductivity, density, viscosity, etc. [7, 78, 108–110] as well as on tribological properties [20, 111, 112] of nanolubricants based on commercially used refrigeration oils. The current literature has a wide variety of studies analyzing the effect of lubricant concentration on heat transfer, pressure loss and thermodynamic properties of oil-refrigerant mixtures [113, 114], for which there are already empirical correlations and theoretical models that allow to predict the thermal behavior of this type of mixtures. Indeed, the effect of nanoparticles on the thermodynamic properties of refrigerant/nanolubricant mixtures has been the subject of a recent study, with so far, few other studies available in the literature [115, 116]. The lack of data, correlations and models regarding thermodynamic properties have limited the amount of theoretical and numerical work to predict the behavior of the refrigeration system operating with nanolubricants. Most of the works involving the modeling of nanolubricants refrigeration systems take only into account the modified thermophysical properties applied to conventional heat transfer correlations or frequently used for nanofluids by the volume or mass concentration. This approach usually ignores the effect of oil fraction and its variations in the thermodynamic properties

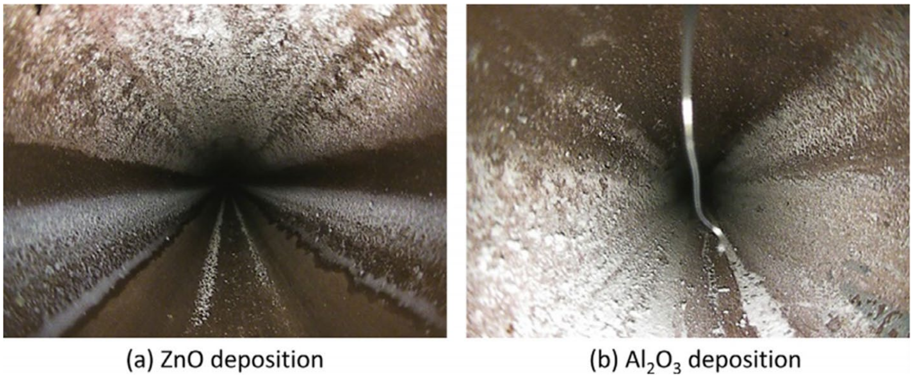
(a) ZnO deposition (b) Al_2O_3 deposition

Fig. 8 Deposition of nanoparticles within the heat transfer surfaces after two-phase flow boiling of nanolubricant/refrigerant mixture. *Source*: [106]

caused by the addition of nanoparticles to the refrigerant [117, 118]. It is important to mention that the rare earth compounds, such as $CeVO_4$ or LaF_3, can be used as nanolubricant. The lubrication mechanism of these compounds is basically the formation of a tribofilm or absorption film. Liu et al. [119] concluded that the wear resistance was improved using the rare earth compound $CeVO_4$ which showed satisfactory anti-wear and friction reduction performance in wear.

5 Conclusions

In this work, an extensive literature review was carried out on the use of nanoparticles as a lubricant additive in refrigeration systems. The main physical mechanisms involved to enhance the system performance were identified. Additionally, the existing studies were classified according to the nature of the nanoparticle. This methodology was applied to identify the advantages of each type of nanomaterial. The analysis revealed that nanolubricants composed of oxides have been extensively studied, especially in reciprocating compressors, and, according to the results found in the literature, they present the highest tendency to increase the performance of refrigeration systems (COP, compressor energy consumption, cooling capacity etc.). Regarding carbon allotropes and composites, few papers were found, compared to oxides, which means that more research is needed to characterize them, even though they already show promising results. Also, there is a lack of experimental data on the application of metallic nanoparticles and it is too early to allow for proper characterization. In this regard, the scarcity of data in the literature stands out, especially for the types of metallic nanoparticles, composites and carbon allotropies. Therefore, the application of composites, metallic and carbon nanomaterials is still open literature regardless of the type of system, refrigerant, lubricant, or compressor. Further application of nanolubricants composed of oxide nanoparticles in refrigeration systems studies will be very interesting for publication if applied in systems with a different type of compressors, rather than reciprocating.

The most used refrigerant was R134a (25 papers), followed by hydrocarbons (9 papers). There are still papers with R22 and with R12. No papers with HFO were found. As far as lubricants are concerned, Mineral Oil was the most used, followed by POE and PAG.

Finally, the major challenges that must be overcome to allow the large-scale application of nanolubricants in refrigeration systems were described. Notably, the long-term stability of the nanoparticle dispersion in the refrigerant/nanolubricant mixture remains the main barrier to be removed before application, combined with the evaluation of the chemical stability and compatibility of nanolubricants with conventionally used materials in refrigeration systems.

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References

1. EIA (2019) International energy outlook 2019 with projections to 2050
2. Coulomb D, Dupon JL, Pichard A (2015) 29th informatory note on refrigeration technologies. The role of refrigeration in the global economy. Note e Note IIR Inf, p 16
3. Saidur R, Kazi SN, Hossain MS, Rahman MM, Mohammed HA (2011) A review on the performance of nanoparticles suspended with refrigerants and lubricating oils in refrigeration systems. Renew Sustain Energy Rev 15:310–323. https://doi.org/10.1016/j.rser.2010.08.018
4. Ahmadi Nadooshan A, Eshgarf H, Afrand M (2018) Evaluating the effects of different parameters on rheological behavior of nanofluids: a comprehensive review. Powder Technol 338:342–353. https://doi.org/10.1016/j.powtec.2018.07.018
5. Sharif MZ, Azmi WH, Mamat R, Shaiful AIM (2018) Mechanism for improvement in refrigeration system performance by using nanorefrigerants and nanolubricants: a review. Int Commun Heat Mass Transf 92:56–63. https://doi.org/10.1016/j.icheatmasstransfer.2018.02.012
6. Fontes DH, Ribatski G, Bandarra Filho EP (2015) Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of nanofluids of carbon nanotubes and diamond in transformer oil. Diam Relat Mater 58:115–121. https://doi.org/10.1016/j.diamond.2015.07.007
7. Kedzierski MA, Brignoli R, Quine KT, Brown JS (2016) Viscosity, density, and thermal conductivity of aluminum oxide and zinc oxide nanolubricants. Int J Refrig 74:3–11. https://doi.org/10.1016/j.ijrefrig.2016.10.003
8. Nair V, Tailor PR, Parekh AD (2016) Nanorefrigerants: a comprehensive review on its past, present and future. Int J Refrig 67:290–307. https://doi.org/10.1016/j.ijrefrig.2016.01.011
9. Babita, Sharma SK, Gupta SM (2016) Preparation and evaluation of stable nanofluids for heat transfer application: a review. Exp Therm Fluid Sci 79:202–212. https://doi.org/10.1016/j.expthermflusci.2016.06.029
10. Das SK, Choi SUS, Yu W, Pradeep T (2007) Nanofluids: science and technology. John Wiley and sons, Hoboken-NJ-USA
11. Sidik NAC, Adamu IM, Jamil MM, Kefayati GHR, Mamat R, Najafi G (2016) Recent progress on hybrid nanofluids in heat transfer applications: a comprehensive review. Int Commun Heat Mass Transf 78:68–79. https://doi.org/10.1016/j.icheatmasstransfer.2016.08.019
12. Choi SUS, Eastman JA (1995) Enhancing thermal conductivity of fluids with nanoparticles. ASME Int Mech Eng Congr Expo 1995:99–106. https://doi.org/10.1115/1.1532008
13. Kumar DS, Elansezhian R (2012) Experimental study on Al_2O_3–R134a nano refrigerant in refrigeration system. Int J Mod Eng Res 2:3927–3929
14. Padmanabhan VMV, Palanisamy S (2012) The use of TiO_2 nanoparticles to reduce refrigerator ir-reversibility. Energy Convers Manag 59:122–132. https://doi.org/10.1016/j.enconman.2012.03.002
15. Wang R, Wu Q, Wu Y (2010) Use of nanoparticles to make mineral oil lubricants feasible for use in a residential air conditioner

employing hydro-fluorocarbons refrigerants. Energy Build 42:2111–2117. https://doi.org/10.1016/j.enbuild.2010.06.023

16. Sharif MZ, Azmi WH, Redhwan AAM, Mamat R, Yusof TM (2017) Performance analysis of SiO_2/PAG nanolubricant in automotive air conditioning system. Int J Refrig 75:204–216. https://doi.org/10.1016/j.ijrefrig.2017.01.004
17. Yu W, Choi SU (2003) The role of the interwell in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model. J Nanoparticle Res 5:167–171
18. Feynman R (1964) The Brownian movement. In: The Feynman lectures on physics, California Institute of Technology, vol I, pp 41–45
19. Hu L, Narayanaswamy A, Chen X, Chen G (2008) Near-field thermal radiation between two closely spaced glass plates exceeding Planck's blackbody radiation law. Appl Phys Lett. https://doi.org/10.1063/12905286
20. Sanukrishna SS, Prakash MJ (2018) Experimental studies on thermal and rheological behaviour of TiO_2–PAG nanolubricant for refrigeration system. Int J Refrig 86:356–372. https://doi.org/10.1016/j.ijrefrig.2017.11.014
21. Knapp MH, Freifeld M (1972) The use of synthetic lubricants in compressors. In: International compressor engineering conference, pp 480–482
22. Lee K, Hwang Y, Cheong S, Choi Y, Kwon L, Lee J et al (2009) Understanding the role of nanoparticles in nano-oil lubrication. Tribol Lett 35:127–131. https://doi.org/10.1007/s11249-009-9441-7
23. Bi S, Guo K, Liu Z, Wu J (2011) Performance of a domestic refrigerator using TiO_2-R600a nano-refrigerant as working fluid. Energy Convers Manag 52:733–737. https://doi.org/10.1016/j.enconman.2010.07.052
24. Alawi OA, Sidik NAC, Kherbeet AS (2015) Nanorefrigerant effects in heat transfer performance and energy consumption reduction: a review. Int Commun Heat Mass Transf 69:76–83. https://doi.org/10.1016/j.icheatmasstransfer.2015.10.009
25. Zou D-B, Wang R-X, Li S-Q, Li X-C (2006) Impact of nanoparticles (n-TiO_2(r)) on the performance of a refrigerating system using HFC/mineral oil as working fluid. J Eng Thermophys 27:37–40
26. Bi S, Shi L, Zhang L (2008) Application of nanoparticles in domestic refrigerators. Appl Therm Eng 28:1834–1843. https://doi.org/10.1016/j.applthermaleng.2007.11.018
27. Górny K, Tyczewski P, Zwierzycki W (2010) Specificity of the lubricating oil operation in the refrigeration compressors. Tribologia 3:63–73
28. Gill J, Singh J, Ohunakin OS, Adelekan DS (2018) Energetic and exergetic analysis of a domestic refrigerator system with LPG as a replacement for R134a refrigerant, using POE lubricant and mineral oil based TiO_2-, SiO_2- and Al_2O_3-lubricants. Int J Refrig 91:122–135. https://doi.org/10.1016/j.ijrefrig.2018.05.010
29. Kumar R, Singh J (2016) Effect of ZnO nanoparticles in R290/R600a (50/50) based vapour compression refrigeration system added via lubricant oil on compressor suction and discharge characteristics. Heat Mass Transf Stoffuebertrag 53:1–9. https://doi.org/10.1007/s00231-016-1921-3
30. Pico DFM, da Silva LRR, Schneider PS, Filho EPB (2019) Performance evaluation of diamond nanolubricants applied to a refrigeration system. Int J Refrig. https://doi.org/10.1016/j.ijrefrig.2018.12.009
31. Krishna Sabareesh R, Gobinath N, Sajith V, Das S, Sobhan CBB, Sabareesh RK et al (2012) Application of TiO_2 nanoparticles as a lubricant-additive for vapor compression refrigeration systems—an experimental investigation. Int J Refrig 35:1989–1996. https://doi.org/10.1016/j.ijrefrig.2012.07.002
32. Alawi OA, Sidik NAC, Beriache M (2015) Applications of nanorefrigerant and nanolubricants in refrigeration, air-conditioning and heat pump systems: a review. Int Commun Heat Mass Transf 68:91–97. https://doi.org/10.1016/j.icheatmasstransfer.2015.08.014
33. Senthilkumar A, Anderson A, Praveen R (2020) Prospective of nanolubricants and nano refrigerants on energy saving in vapour compression refrigeration system: a review. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.06.416
34. Azmi WH, Sharif MZ, Yusof TM, Mamat R, Redhwan AAM (2017) Potential of nanorefrigerant and nanolubricant on energy saving in refrigeration system: a review. Renew Sustain Energy Rev 69:415–428. https://doi.org/10.1016/j.rser.2016.11.207
35. Bhattad A, Sarkar J, Ghosh P (2018) Improving the performance of refrigeration systems by using nanofluids: a comprehensive review. Renew Sustain Energy Rev 82:3656–3669. https://doi.org/10.1016/j.rser.2017.10.097
36. Yang L, Jiang W, Ji W, Mahian O, Bazri S, Sadri R et al (2020) A review of heating/cooling processes using nanomaterials suspended in refrigerants and lubricants. Int J Heat Mass Transf 153:119611. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119611
37. Yıldız G, Ağbulut Ü, Gürel AE (2021) A review of stability, thermophysical properties and impact of using nanofluids on the performance of refrigeration systems. Int J Refrig 129:342–364. https://doi.org/10.1016/j.ijrefrig.2021.05.016
38. Bharathwaj RP, Shaik J, Raju JJ, Padmanathan P, Satheesh A (2021) A critical review on nanorefrigerants: boiling, condensation and tribological properties. Int J Refrig 128:139–152. https://doi.org/10.1016/j.ijrefrig.2020.12.027
39. Che Sidik NA, Mahmud Jamil M, Aziz Japar WMA, Muhammad AI (2017) A review on preparation methods, stability and applications of hybrid nanofluids. Renew Sustain Energy Rev 80:1112–1122. https://doi.org/10.1016/j.rser.2017.05.221
40. Sofiah AGN, Samykano M, Pandey AK, Kadirgama K, Sharma K, Saidur R (2021) Immense impact from small particles: review on stability and thermophysical properties of nanofluids. Sustain Energy Technol Assess 48:101635. https://doi.org/10.1016/j.seta.2021.101635
41. Adun H, Kavaz D, Dagbasi M (2021) Review of ternary hybrid nanofluid: synthesis, stability, thermophysical properties, heat transfer applications, and environmental effects. J Clean Prod 328:129525. https://doi.org/10.1016/j.jclepro.2021.129525
42. Said Z, Sundar LS, Tiwari AK, Ali HM, Sheikholeslami M, Bellos E et al (2021) Recent advances on the fundamental physical phenomena behind stability, dynamic motion, thermophysical properties, heat transport, applications, and challenges of nanofluids. Phys Rep 946:1–94. https://doi.org/10.1016/j.physrep.2021.07.002
43. Asadi A, Aberoumand S, Moradikazerouni A, Pourfattah F, Żyła G, Estellé P et al (2019) Recent advances in preparation methods and thermophysical properties of oil-based nanofluids: a state-of-the-art review. Powder Technol 352:209–226. https://doi.org/10.1016/j.powtec.2019.04.054
44. Ajayi OO, Useh OO, Banjo SO, Oweoye FT, Ogbonnaya M, Okokpujie IP et al (2018) Investigation of the heat transfer effect of Ni/R134a nanorefrigerant in a mobile hybrid powered vapour compression refrigerator. IOP Conf Ser Mater Sci Eng 391:012001. https://doi.org/10.1088/1757-899X/391/1/012001
45. Yilmaz AC (2020) Performance evaluation of a refrigeration system using nanolubricant. Appl Nanosci 10:1667–1678. https://doi.org/10.1007/s13204-020-01258-5
46. Fu L, Wang R, Cong W, Li Q, Wu Y (2008) Experimental study on performance of refrigerator using nano-particle additive. J Xi'an Jiaotong Univ 42:852–854
47. Jwo C, Jeng L, Teng T, Chang H, Jwo C (2009) Effects of nanolubricant on performance of hydrocarbon refrigerant system. J Vac

Sci Technol B Microelectron Nanometer Struct Process Meas. https://doi.org/10.1116/1.3089373

48. Subramani N, Prakash MJM (2012) Experimental studies on a vapour compression system using nanorefrigerants. Int J Eng Sci Technol 3:95–102. https://doi.org/10.4314/ijest.v3i9.8
49. Subramani N, Mohan A, Prakash MJ (2013) Performance studies on a vapour compression refrigeration system using nanolubricant. Int J Innov Res Sci Eng Technol 2:522–530
50. Kumar RR, Sridhar K, Narasimha M (2013) Heat transfer enhancement in domestic refrigerator using R600a/mineral oil/nano-Al_2O_3 as working fluid. Int J Comput Eng Res 3:42–50
51. Yusof TM, Arshad A, Suziyana MD, Chui LG, Basrawi MF (2015) Experimental study of a domestic refrigerator with POE-Al_2O_3 nanolubricant. Int J Automot Mech Eng 11:2243–2252. https://doi.org/10.15282/ijame.11.2015.7.0188
52. Soliman AMA, Abdel Rahman AK, Ookawara S (2018) Enhancement of vapor compression cycle performance using nanofluids. J Therm Anal Calorim. https://doi.org/10.1007/s10973-018-7623-y
53. Shareef AS, Azziz HN, Hadi HS (2018) Experimental study: the effects of using nano-lubrication on the performance of refrigeration systems. IOP Conf Ser Mater Sci Eng 433:012052. https://doi.org/10.1088/1757-899X/433/1/012052
54. Bondre D, Joshi A, Shinde T, Deshmukh A, Dhanawade K (2019) Experimental performance and analysis of domestic refrigeration system using nano-refrigerants. Proceedings of international conference on intelligent manufacturing and automation. Springer, Singapore, pp 389–399. https://doi.org/10.1007/978-981-13-2490-1
55. Nair V, Parekh AD, Tailor PR (2020) Experimental investigation of a vapour compression refrigeration system using R134a/Nano-oil mixture. Int J Refrig 112:21–36. https://doi.org/10.1016/j.ijrefrig.2019.12.009
56. Vara Prasad GVVS, Dilip Kumar K (2018) Employing magnetic field to liquid channel of nano lubricant (CuO & PAG oil) rigged VCR system by using R134a refrigerant. Mater Today Proc 5:20518–20527. https://doi.org/10.1016/j.matpr.2018.06.429
57. Kumar R, Singh J, Kundal P (2018) Effect of CuO nanolubricant on compressor characteristics and performance of LPG based refrigeration cycle: experimental investigation. Heat Mass Transf 54:1405–1413
58. Anish M, Senthil Kumar G, Beemkumar N, Kanimozhi B, Arunkumar T (2018) Performance study of a domestic refrigerator using CuO/Al_2O_3-R22 nanorefrigerant as a working fluid. Int J Ambient Energy. https://doi.org/10.1080/01430750.2018.1451376
59. Bandgar MS, Kolhe KP, Ragit SS (2016) An experimental investigation of VCRS using R134a/POE oil/mineral oil/nano-SiO_2 as working fluid. J Emerg Technol Innov Res 3:4–9
60. Ohunakin OS, Adelekan DS, Gill J, Atayero AA, Atiba OE, Okokpujie IP et al (2018) Performance of a hydrocarbon driven domestic refrigerator based on varying concentration of SiO_2 Nano-lubricant. Int J Refrig 94:59–70. https://doi.org/10.1016/J.IJREFRIG.2018.07.022
61. Sajumon KT, Jubin VJ, Sreejith S, Aghil VM, Sreeraj Kurup PN, Sasi S (2013) Performance analysis of nanofluid based lubricant. Int J Innov Res Sci Eng Technol 2:832–838
62. Fedele L, Colla L, Scattolini M, Bellomare F, Bobbo S (2014) Nanofluids application as nanolubricants in heat pumps systems. In: International refrigeration and air conditioning conference, Purdue University, West Lafayette, IN, USA
63. Hussen HA (2014) Experimental investigation for TiO_2 nanoparticles as a Lubricant-additive for a compressor of window type air-conditioner system. J Eng 20:61–72
64. Babu AM, Nallusamy S, Rajan K (2016) Experimental analysis on vapour compression refrigeration system using nanolubricant with HFC-134a refrigerant. Nano Hybrids 9:33–43. https://doi.org/10.4028/www.scientific.net/NH.9.33
65. Sutandi T, Lukitobudi AR, Sumeru K, Imbang Trijahjono R, Sukri MF (2018) Performance of residential air conditioning using nanoparticles as additive in the synthetic lubricant. In: Proceedings of the 9th international conference on thermofluids 2017, vol 2001, AIP Publishing.https://doi.org/10.1063/1.5050017
66. Jatinder G, Ohunakin OS, Adelekan DS, Atiba OE, Daniel AB, Singh J et al (2019) Performance of a domestic refrigerator using selected hydrocarbon working fluids and TiO_2–MO nanolubricant. Appl Therm Eng. https://doi.org/10.1016/j.applthermaleng.2019.114004
67. Abdur Razzaq ME, Ahamed JU (2020) Thermodynamic analysis of an air conditioner using R22/HC blend with TiO_2/Mineral oil nanolubricant to retrofit R22/POE oil. Results Eng. https://doi.org/10.1016/j.rineng.2020.100166
68. Sendil Kumar D, Elansezhian R (2014) ZnO nanorefrigerant in R152a refrigeration system for energy conservation and green environment. Front Mech Eng 9:75–80. https://doi.org/10.1007/s11465-014-0285-y
69. Shah TR, Koten H, Ali HM (2020) Chapter 5—performance effecting parameters of hybrid nanofluids. In: Ali HM (ed) Hybrid nanofluids for convection heat transfer. Academic Press, pp 179–213. https://doi.org/10.1016/B978-0-12-819280-1.00005-7.
70. Saravanan K, Vijayan R (2018) Performance of Al_2O_3/TiO_2 nano composite particles in domestic refrigerator. J Exp Nanosci 13:244–256. https://doi.org/10.1080/17458080.2018.1491066
71. Chauhan SS (2020) Performance evaluation of ice plant operating on R134a blended with varied concentration of Al_2O_3–SiO_2/PAG composite nanolubricant by experimental approach. Int J Refrig 113:196–205. https://doi.org/10.1016/j.ijrefrig.2020.01.021
72. George N, Nair AB, Varghese N, Joseph R (2021) 8—Utilization of carbon allotropes with special reference to carbon nanotubes and graphene for the high performance of natural rubber. In: Kohjiya S, Ikeda Y (eds) Chemistry, manufacture, and application of natural rubber, 2nd edn. Woodhead Publishing, pp 203–246. https://doi.org/10.1016/B978-0-12-818843-9.00014-X.
73. Tanzi MC, Farè S, Candiani G (2019) Chapter 1—Organization, structure, and properties of materials. In: Tanzi MC, Farè S, Candiani G (eds) Foundations of biomaterials engineering. Academic Press, pp 3–103. https://doi.org/10.1016/B978-0-08-101034-1.00001-3
74. Holkar CR, Jain SS, Jadhav AJ, Pinjari DV (2018) Chapter 14—Scale-up technologies for advanced nanomaterials for green energy: feasibilities and challenges. In: Bhanvase BA, Pawade VB, Dhoble SJ, Sonawane SH, Ashokkumar M (eds) Nanomaterials for green energy. Elsevier, pp 433–455. https://doi.org/10.1016/B978-0-12-813731-4.00014-X
75. Shoala T (2020) 13—Carbon nanostructures: detection, controlling plant diseases and mycotoxins. In: Abd-Elsalam KA (ed) Carbon Nanomaterials for Agri-Food and Environmental Applications. Elsevier, pp 261–277. https://doi.org/10.1016/B978-0-12-819786-8.00013-X
76. Maruyama T (2021) Chapter 6—Carbon nanotubes. In: Thomas S, Sarathchandran C, Ilangovan SA, Moreno-Piraján JC (eds) Handbook of Carbon-Based Nanomaterials. Elsevier, pp 299–319. https://doi.org/10.1016/B978-0-12-821996-6.00009-9
77. Zhai W, Srikanth N, Kong LB, Zhou K, Bing L, Zhou K (2017) Carbon nanomaterials in tribology. Carbon N Y 119:150–171. https://doi.org/10.1016/j.carbon.2017.04.027

78. Cárdenas Gómez AO, Hoffmann ARK, Bandarra Filho EP (2015) Experimental evaluation of CNT nanofluids in single-phase flow. Int J Heat Mass Transf 86:277–287. https://doi.org/10.1016/j.ijheatmasstransfer.2015.02.066
79. Yazid MNAWM, Sidik NAC, Yahya WJ (2017) Heat and mass transfer characteristics of carbon nanotube nanofluids: a review. Renew Sustain Energy Rev 80:914–941. https://doi.org/10.1016/j.rser.2017.05.192
80. Abbas M, Walvekar RG, Hajibeigy MT, Farhood S (2013) Efficient Air-condition unit by using nano-refrigerant. Eng Undergrad Res Catal Conf, pp 87–88
81. Xing M, Wang R, Yu J (2014) Application of fullerene C_{60} nano-oil for performance enhancement of domestic refrigerator compressors. Int J Refrig 40:398–403. https://doi.org/10.1016/j.ijrefrig.2013.12.004
82. Kamaraj N, Babu AM (2016) Experimental analysis of vapour compression refrigeration system using the refrigerant with nano particles. In: International conference on engineering innovation solutions, pp 16–25
83. Moroz SA, Khliyeva Y, Lukianov NN, Zhelezny VP (2016) The influence of the compressor oil viscosity and fullerenes C_{60} additives in the oil on the energy efficiency of refrigeration compressor system. Refrig Technol Eng. https://doi.org/10.21047/1606-4313-2016-16-1-41-46
84. Lou JF, Zhang H, Wang R (2015) Experimental investigation of graphite nanolubricant used in a domestic refrigerator. Adv Mech Eng. https://doi.org/10.1177/1687814015571011
85. Marcucci Pico DF, da Silva LRRR, Hernandez Mendoza OS, Bandarra Filho EP, Hernandez OS, Bandarra Filho EP et al (2020) Experimental study on thermal and tribological performance of diamond nanolubricants applied to a refrigeration system using R32. Int J Heat Mass Transf 152:119493. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119493
86. Yang S, Cui X, Zhou Y, Chen C (2020) Study on the effect of graphene nanosheets refrigerant oil on domestic refrigerator performance. Int J Refrig 110:187–195. https://doi.org/10.1016/j.ijrefrig.2019.11.008
87. Babarinde TO, Akinlabi SA, Madyira DM, Ekundayo FM (2020) Enhancing the energy efficiency of vapour compression refrigerator system using R600a with graphene nanolubricant. Energy Rep 6:1–10. https://doi.org/10.1016/j.egyr.2019.11.031
88. Choi TJ, Kim DJ, Jang SP, Park S, Ko S (2021) Effect of polyolester oil-based multiwalled carbon-nanotube nanolubricant on the coefficient of performance of refrigeration systems. Appl Therm Eng 192:116941. https://doi.org/10.1016/j.applthermaleng.2021.116941
89. Luo G, Du L, Wang Y, Wang K. Composite Nanoparticles (2015) In: Li D (ed) Encyclopedia of Microfluidics and Nanofluidics. Springer, New York, pp 453–460. https://doi.org/10.1007/978-1-4614-5491-5_243
90. Nabil MF, Azmi WH, Hamid KA, Zawawi NNM, Priyandoko G, Mamat R (2017) Thermo-physical properties of hybrid nanofluids and hybrid nanolubricants: a comprehensive review on performance. Int Commun Heat Mass Transf 83:30–39. https://doi.org/10.1016/j.icheatmasstransfer.2017.03.008
91. Jia T, Wang R, Xu R (2014) Performance of $MoFe_2O_4$–$NiFe_2O_4$/fullerene-added nano-oil applied in the domestic refrigerator compressors. Int J Refrig 45:120–127. https://doi.org/10.1016/j.ijrefrig.2014.06.001
92. Wang R, Zhang Y, Liao Y (2017) Performance of rolling piston type rotary compressor using fullerenes (C_{70}) and $NiFe_2O_4$ nanocomposites as lubricants additives. Front Energy. https://doi.org/10.1007/s11708-017-0453-y
93. Montgomery DC (2012) Design and analysis of experiments. Technometrics. https://doi.org/10.1198/tech.2006.s372
94. Kedzierski MA (2013) Viscosity and density of aluminum oxide nanolubricant. Int J Refrig 36:1333–1340. https://doi.org/10.1016/j.ijrefrig.2013.02.017
95. Wan Q, Jin Y, Sun P, Ding Y (2015) Tribological behaviour of a lubricant oil containing boron nitride nanoparticles. Procedia Eng 102:1038–1045. https://doi.org/10.1016/j.proeng.2015.01.226
96. Lahouij I, Vacher B, Martin JM, Dassenoy F (2012) IF-MoS_2 based lubricants: influence of size, shape and crystal structure. Wear 296:558–567. https://doi.org/10.1016/j.wear.2012.07.016
97. Liñeira del Río JM, Guimarey MJG, Comuñas MJP, López ER, Amigo A, Fernández J (2018) Thermophysical and tribological properties of dispersions based on graphene and a trimethylolpropane trioleate oil. J Mol Liq 268:854–866. https://doi.org/10.1016/j.molliq.2018.07.107
98. Kole M, Dey TK (2013) Enhanced thermophysical properties of copper nanoparticles dispersed in gear oil. Appl Therm Eng 56:45–53. https://doi.org/10.1016/j.applthermaleng.2013.03.022
99. Yu W, Huaqing X (2011) A review on nanofluids: preparation stability mechanisms and applications. J Nanomater 87:228–240. https://doi.org/10.1155/2012/435873
100. Ohmae N, Martin JM (2008) Nanolubricants. John Wiley & Sons, West Sussex, England
101 Bi SS, Shi L, Zhang LL (2008) Application of nanoparticles in domestic refrigerators. Appl Therm Eng 28:1834–1843
102. Ding G, Peng H, Jiang W, Gao Y (2009) The migration characteristics of nanoparticles in the pool boiling process of nanorefrigerant and nanorefrigerant-oil mixture. Int J Refrig 32:114–123. https://doi.org/10.1016/j.ijrefrig.2008.08.007
103. Lin L, Peng H, Chang Z, Ding G (2017) Experimental investigation on TiO_2 nanoparticle migration from refrigerant—oil mixture to lubricating oil during refrigerant dryout. Int J Refrig 77:75–86. https://doi.org/10.1016/j.ijrefrig.2017.02.026
104. Lin L, Peng H, Chang Z, Ding G (2017) Experimental research on degradation of nanolubricant-refrigerant mixture during continuous alternation processes of condensation and evaporation. Int J Refrig 76:97–108. https://doi.org/10.1016/j.ijrefrig.2016.12.021
105. Lin L, Chang Z, Ding G (2019) Resuspension of deposited nanoparticles during pool boiling. Int J Heat Mass Transf 130:230–239. https://doi.org/10.1016/j.ijheatmasstransfer.2018.10.092
106. Deokar PS, Cremaschi L (2020) Effect of nanoparticle additives on the refrigerant and lubricant mixtures heat transfer coefficient during in-tube single-phase heating and two-phase flow boiling. Int J Refrig 110:142–152. https://doi.org/10.1016/j.ijrefrig.2019.10.018
107. Kruse H, Schroeder M (1985) Fundamentals of lubrication in refrigerating systems and heat pumps. Int J Refrig 8:347–355. https://doi.org/10.1016/0140-7007(85)90030-1
108. Lin L, Kedzierski MA (2018) Specific heat of aluminum-oxide nanolubricants. Int J Heat Mass Transf 126:1168–1176. https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.077
109. Kedzierski MA (2012) Viscosity and density of CuO nanolubricant. Int J Refrig 35:1997–2002. https://doi.org/10.1016/j.ijrefrig.2012.06.012
110. Redhwan AAM, Azmi WH, Sharif MZ, Zawawi NNM (2017) Thermal conductivity enhancement of Al_2O_3 and SiO_2 nanolubricants for application in automotive air conditioning (AAC) system. In: MATEC web conference, vol 90, p 01051. https://doi.org/10.1051/matecconf/20179001051
111. Choi Y, Lee C, Hwang Y, Park M, Lee J, Choi C et al (2009) Tribological behavior of copper nanoparticles as additives in oil. Curr Appl Phys 9:e124–e127. https://doi.org/10.1016/j.cap.2008.12.050
112. Sanukrishna SS, Vishnu S, Krishnakumar TS, Prakash MJ (2018) Effect of oxide nanoparticles on the thermal, rheological and

tribological behaviours of refrigerant compressor oil: an experimental investigation. Int J Refrig 90:32–45. https://doi.org/10.1016/j.ijrefrig.2018.04.006

113. Bandarra Filho EP, Cheng L, Thome JR (2009) Flow boiling characteristics and flow pattern visualization of refrigerant/lubricant oil mixtures. Int J Refrig 32:185–202. https://doi.org/10.1016/j.ijrefrig.2008.06.013
114. Youbi-Idrissi M, Bonjour J (2008) The effect of oil in refrigeration: Current research issues and critical review of thermodynamic aspects. Int J Refrig 31:165–179. https://doi.org/10.1016/j.ijrefrig.2007.09.006
115. Zhelezny V, Khliyeva O, Lukianov M, Motovoy I, Ivchenko D, Faik A et al (2019) Thermodynamic properties of isobutane/mineral compressor oil and isobutane/mineral compressor oil/fullerenes C_{60} solutions. Int J Refrig 106:153–162. https://doi.org/10.1016/j.ijrefrig.2019.06.011
116. Zhelezny PV, Zhelezny VP, Procenko DA, Ancherbak SN (2007) An experimental investigation and modelling of the thermodynamic properties of isobutane e compressor oil solutions: some aspects of experimental methodology. Int J Refrig. https://doi.org/10.1016/j.ijrefrig.2006.09.007
117. Fadhilah SA, Marhamah RS, Izzat AHM (2014) Copper oxide nanoparticles for advanced refrigerant thermophysical properties: mathematical modeling. J Nanoparticles 2014:1–5. https://doi.org/10.1155/2014/890751
118. Coumaressin T, Palaniradja K (2014) Performance analysis of a refrigeration system using nano fluid. Int J Adv Mech Eng 4:459–470
119. Liu F, Shao X, Yin Y, Zhao L, Shao Z, Liu X, Meng X (2011) Shape controlled synthesis and tribological properties of $CeVO_4$ nanoparticles as lubricating additive. J Rare Earths 29:688–691
120. Redhwan AAM, Azmi WH, Sharif MZ, Mamat R (2016) Development of nanorefrigerants for various types of refrigerant based: a comprehensive review on performance. Int Commun Heat Mass Transf 76:285–293. https://doi.org/10.1016/j.icheatmasstransfer.2016.06.007
121. Jwo CSS, Jeng LYY, Teng TPP, Chang H (2009) Effects of nanolubricant on performance of hydrocarbon refrigerant system. J Vac Sci Technol B Microelectron Nanom Struct Process Measur Phenom 27:1473–1477. https://doi.org/10.1116/1.3089373
122. Almeida IMG (2015) Análise tribo-termodinâmica da aplicação de nanopartículas de Al_2O_3 como aditivo lubrificante. Universidade Fereal do Rio Grande do Norte