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ORIGINAL ARTICLE

Evaluation of the energy performance of refrigeration systems using nanofluids: a systematic and critical review

ABSTRACT: In recent years, nanotechnology has emerged in the development of nanofluids. Research aimed at applying the nanorefrigerants and nanolubricants in vapor compression refrigeration systems is arousing much interest in the scientific community. This is thanks to the effect of the nanoparticles (NPs) in the thermodynamic properties of the base fluid, providing an improvement in the thermal exchanges of the system. In this context, the present work aims to carry out a systematic literature review, addressing the energetic influence of the applications of nanofluids in vapor compression refrigeration systems, highlighting parameters that can directly affect the performance of the system, such as compressor energy consumption, cooling capacity, and the coefficient of performance of the system (COP). In order to cover the most relevant works on this subject, the ordination method was used as a methodology for the selection and classification of the bibliographic database. It is possible to affirm that the use of NPs in refrigeration systems reduces the system's energy consumption, providing an increase in its energy performance. Furthermore, it was possible to verify that the use of nanofluids increases the cooling capacity in refrigeration systems by vapor compression, making them potential candidates for replacing conventional lubricants and refrigerants.

Keywords: energy efficiency; energy performance; nanolubricants; nanorefrigerants; refrigeration system.

Avaliação do desempenho energético de sistemas de refrigeração utilizando nanofluidos: uma revisão sistemática e críticas

RESUMO: *Nos últimos anos, a nanotecnologia surgiu no desenvolvimento de nanofluidos. Pesquisas com o objetivo de aplicar os nanorrefrigerantes*

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e nanolubrificantes em sistemas de refrigeração por compressão de vapor estão despertando interesse na comunidade científica. Isso se deve ao efeito das nanopartículas (NPs) nas propriedades termodinâmicas do fluido base, proporcionando uma melhoria nas trocas térmicas do sistema. Nesse contexto, o presente trabalho tem como objetivo realizar uma revisão sistemática da literatura, abordando a influência energética das aplicações de nanofluidos em sistemas de refrigeração por compressão de vapor, destacando parâmetros que podem afetar diretamente o desempenho do sistema, tais como consumo de energia do compressor, capacidade de refrigeração e o coeficiente de desempenho do sistema (COP). De forma a abranger os trabalhos mais relevantes sobre o assunto, foi utilizado o método de ordenação como metodologia de seleção e classificação da base de dados bibliográfica. É possível afirmar que o uso de NPs em sistemas de refrigeração reduz o consumo de energia do sistema, proporcionando um aumento no seu desempenho energético. Além disso, foi possível verificar que o uso de nanofluidos aumenta a capacidade de resfriamento em sistemas de refrigeração por compressão de vapor, tornando-os possíveis candidatos à substituição de lubrificantes e refrigerantes convencionais.

Palavras-chave: *desempenho energético; eficiência energética; nanolubrificantes; nanorrefrigerantes; sistema de refrigeração.*

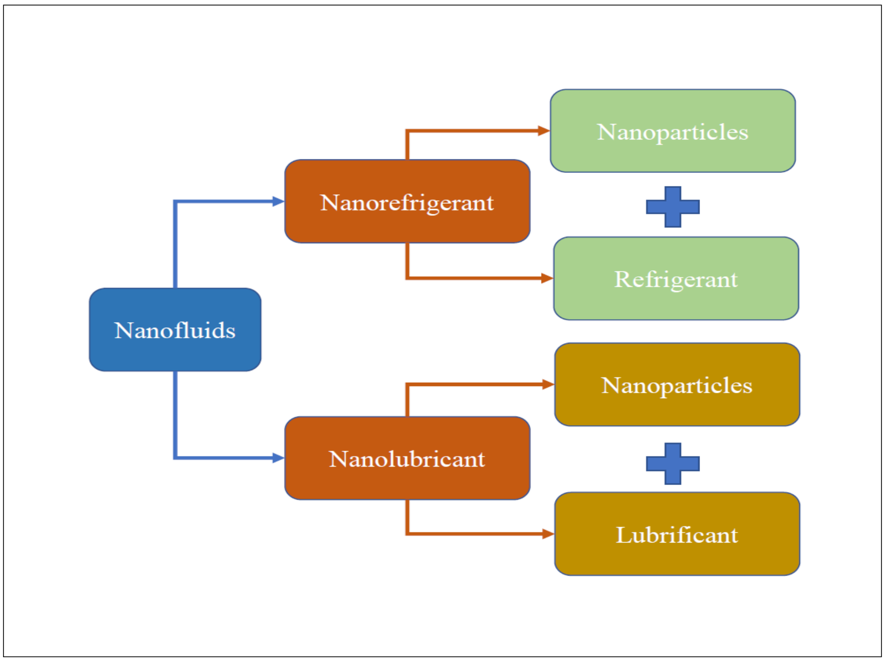
1 Introduction

Global electricity demands are continually increasing due to population and economic growth. According to the Ministry of Mines and Energy, in January 2021, Brazil had a consumption of electricity 1.9% higher than in January 2020 (BRASIL, 2021). Within this energy demand, activities related to refrigeration represent a significant part of this consumption, which are present in industrial, commercial, transport, and residential sectors. Reducing energy consumption is one of the main challenges in refrigeration systems, and one way to overcome this issue is the use of new technologies such as nanotechnology. Law 10.295/2001 aims to promote the rational use of energy, with the goal of efficient allocation of energy resources and the preservation of the environment. According to Cardoso (2017), the impact of this law on refrigeration and air conditioning equipment generated energy savings of around 104.8 GWh. The use of heat, previously wasted, can be used to activate refrigeration systems by vapor absorption (SOUZA *et al*., 2020). This coupling increases the overall efficiency of energy trigeneration systems, as described by Marques *et al*. (2020).

Lubricating and refrigerating fluids used in the refrigeration systems have thermodynamic and tribological properties that can directly influence the system performance. Such properties as thermal conductivity and viscosity can be modified with the addition of nanoparticles (NPs) to the fluid, giving rise to a new class of materials known as nanofluids (CHOI; EASTMAN, 1995). Studies indicate that the use of nanoparticles in refrigeration systems increases the cooling capacity of the system, considerably decreases the compressor's work, and provides an increase in the coefficient of performance – COP (SENTHILKUMAR; ANDERSON; PRAVEEN, 2020). Among the various types of existing NPs, those commonly used are metals, like aluminum (Al), silver (Ag), copper (Cu) and Iron (Fe). Also, oxides like aluminum oxide (Al_2O_3), titanium dioxide (TiO_2); nitrides like hexagonal boron nitride (h-BN); and carbon compounds: graphene and diamond (BABU; KUMAR; RAO, 2017).

Normally, nanofluids for application in refrigeration systems can be prepared by two methods, as shown in Figure 1. The first method consists of dispersing solid NPs in a refrigerant fluid, creating nanorefrigerants. The second method results in the dispersion of NPs in a lubricating fluid, giving rise to nanolubricants. Although the principles of the synthesis of nanolubricants and nanorefrigerants are similar, their applications could be completely different. The role of the nanolubricants is the improvement of their tribological properties, while nanorefrigerants affect the thermal exchange capacity.

Figure 1 ▶
Common methods of preparing nanofluids for refrigeration systems. *Source: adapted from Sharif et al. (2018)*



Oliveira *et al*. (2021) carried out a study on the thermo-hydraulic performance of nanofluids in thermal exchange processes in refrigeration systems. The nanofluids were prepared using multi-walled carbon nanotube (MWCNT, a type of carbon nanotubes) dispersed in distilled water. A maximum increase of 5.4% for the convective heat transfer coefficient in a sample with a final concentration of 0.01% by volume of nanoparticles was obtained.

Lee *et al*. (2009) evaluated nanolubricants formed by fullerene NPs dispersed in mineral oil and observed a 90% decrease in the friction coefficient of the lubricating fluid with the use of NPs, concluding that the compressor will have greater efficiency and reliability. A study on performance improvement mechanisms by vapor compression refrigeration systems using nanorefrigerants and nanolubricants was carried out by Sharif *et al*. (2018). They found that the nanolubricants reduce the friction and the wear rate in the compressor compared to the system which only uses lubricant without NPs.

As the use of nanotechnology in refrigeration systems is a noble research topic, this work aims to carry out a systematic literature review, addressing the energetic influence of the use of nanofluids in a vapor compression refrigeration system, taking into account key parameters that directly influence system performance, such as compressor energy consumption, cooling capacity, and system COP.

The article is organized as follows: section 2 deals with the methodology applied for the development of the work; section 3 brings the results of the bibliometric review and qualitative comparisons; and the last section brings the conclusions and perspectives of the authors.

2 Methodology

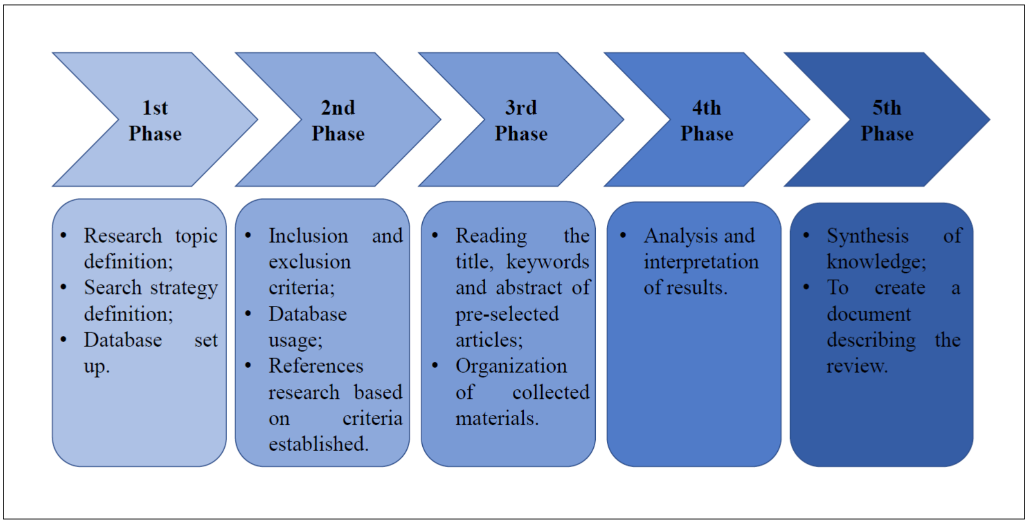
This work is split over the following steps: (1) brainstorming: definition of the theme and objective to be approached; (2) establishment of inclusion and exclusion criteria for articles; (3) selection of information to be collected in the researched articles; (4) analysis and discussion of the information obtained; and (5) presentation of the literature review. To select a bibliographic portfolio composed of relevant publications, the ordination method was used. This consists of a systematic methodology for identifying and classifying scientific articles in relation to their relevance through factors such as impact factor, year of publication, and the number of citations (PAGANI; KOVALESKI; RESENDE, 2015).

A systematic search was carried out with the Google Scholar tool, using English as the search language, in order to cover articles of international relevance. The following descriptors were used: Compression Refrigeration System, Nanolubricant, Nanorefrigerant, Energy Saving and Coefficient of Performance, in addition to using the Boolean operators AND and OR to find the largest number of works related to the use of nanofluids in refrigeration systems. The work carried out by Fonseca *et al*. (2021) was used as a methodological basis.

As an inclusion criterion, articles that presented research related to the use of NPs in refrigeration systems published in the period from 2016 to 2021 were considered. Also serving as a selection criterion, only articles published in the Elsevier and Springer publishers were considered, as they are a reference in the area of science and technology and are known for their global reliability. As an exclusion criterion, texts that are not scientific articles, review articles, and also those publications that did not adhere to the theme of the influence of nanofluids on the energy performance of vapor compression refrigeration systems were disregarded. Reference lists of selected articles from the database were also consulted in order to find new studies to include in the review.

Figure 2 expresses the steps performed in the execution of this work. The first step aims to define the topic to be addressed, in addition to determining which search strategies and means were used to obtain the bibliographic base. The second and third steps are relevant to the process of searching and screening the references used in this review, following the previously defined inclusion and exclusion criteria. The references used in the selected articles also underwent an analysis process in order to add more information and to reinforce the theoretical basis of this study. In the fourth step, all selected references were carefully reviewed, focusing on the analysis and interpretation of the results presented in each work. At this stage, the following points were considered: the concentration and type of NPs as well as the refrigerants types used in the system. The fifth step consists of writing the present article, synthesizing the knowledge acquired throughout the research process, and analysis of the results.

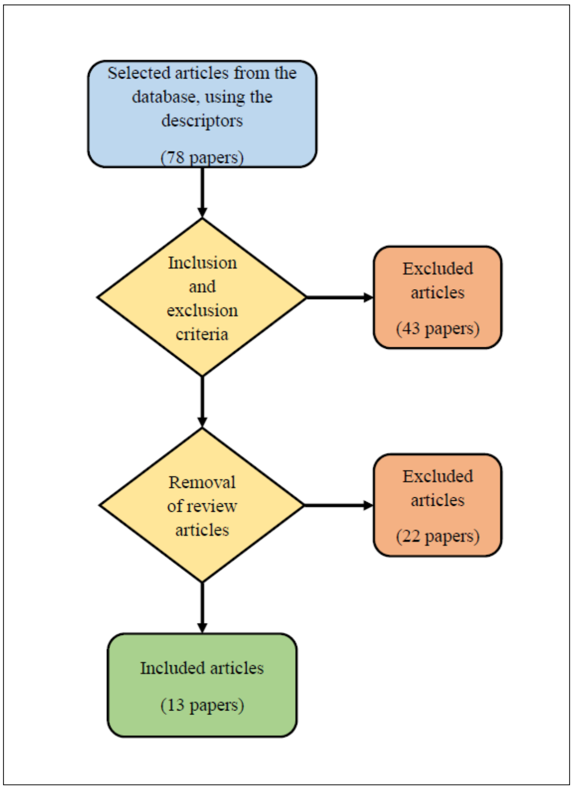
Figure 2 ▶
Steps of the methodology used in this review article.
Source: prepared by the authors



3 Results and discussion

The flowchart in Figure 3 shows the result of the steps in the process of collecting and sorting the bibliographic database. After searching the databases for references using descriptors and inclusion criteria given in previous section, a total of 78 research articles were selected. In the process of screening and applying the exclusion criteria, 13 studies were selected to form the theoretical basis for the current review.

Figure 3 ▶
Results of the stages of the collection and sorting process.
Source: prepared by the authors



The studies included were analyzed in their entirety in order to observe the energy behavior of the systems after the addition of NPs. In order to conduct such analysis, the following themes were considered: system energy consumption, COP, cooling capacity, and pull-down time; this last parameter corresponds to the time necessary for the system to reach the desired temperature value. Manikanden and Avinash (2019) carried out a study on the effect of pure and Ag-doped copper oxide (CuO) NPs on the performance of a refrigeration system that uses R290 as the refrigerant. They found that the energy consumption of the system with the use of CuO NPs was 15% lower compared to the use of pure R290. This percentage increased to 28% with the use of silver-doped CuO NPs. It was also observed that the cooling effect of the system using pure R290, CuO NPs, and Ag-doped CuO NPs had the respective values of 50 W, 73 W, and 163 W. The system's COP was calculated using the reading of an energy meter and the cooling load, noting a 6% increase in the COP with the use of Ag-doped CuO NPs compared to pure CuO NPs.

An investigation into the effect of zinc oxide (ZnO) NPs in a vapor compression refrigeration system was carried out by Kumar and Singh (2017) using a combination of R290 and R600a in a 50/50 ratio. The dispersion of NPs was made in mineral oil with a concentration ranging from 0.2% to 1.0% by weight. It was found that the energy consumption by the compressor using pure mineral oil and mineral oil having 0.8% of ZnO NPs was 0.1323 KW and 0.1224 KW, respectively. The authors found that compressor energy consumption was reduced by 3.40% to 7.48%, depending on the concentration of NPs in the lubricating oil. In addition, the COP increased by around 46% in the system having 0.8% of ZnO compared to pure mineral oil. A similar result was obtained by Senthilkumar *et al*. (2021) in an experimental investigation of the use of a nanolubricant composed of ZnO and silicon dioxide (SiO_2) particles in a vapor compression refrigeration system. The addition of the hybrid nanolubricant to the system increased the COP by 42% compared to the system without nanolubricants. It was observed that the maximum compressor work without the use of nanolubricant was 130 W and 115 W, respectively, for the configurations with 40 g and 60 g of R600a. The minimum compressor work was 78 W for the configuration using 0.6 g/L of ZnO and SiO_2 NPs and 60 g of refrigerant.

A study on the performance of domestic refrigerators using TiO_2 NPs dispersed in mineral oil was carried out by Jatinder *et al*. (2019). The parameters analyzed in their study included compressor energy consumption, cooling capacity, COP, compressor discharge temperature, and pull-down time. In addition to the different loads of R600a, three different concentrations of TiO_2 dispersed in mineral oil were also applied. For the configuration of 0.2 g/L of TiO_2 and different loads of R600a, the energy consumption of the system was about 1.94% to 33.33% lower than the refrigerant based on liquefied petroleum gas (LPG). A greater cooling effect (205.34 W) and COP of 4.99 were observed for the 40 g charge of R600 with a concentration of 0.2 g/L of TiO_2. This improvement in system performance can be explained by the significant change in the thermophysical properties of the lubricant in the compressor. Adelekan *et al*. (2019b) also observed the similar impact on the performance of a refrigeration system due to the increase in TiO_2 concentration, using R600a as the refrigerant. They found that the compressor work decreased and a maximum value of 4.99 for the COP of the system with a concentration of 0.1 g/L of TiO_2 in 40 g of R600a was achieved.

Mohan *et al*. (2020) carried out an experimental study on the exergetic performance of a vapor compression refrigeration system using carbon nanotubes (CNT), gold NPs, and chloroauric acid ($HAuCl_4$) suspended in polyalkylene glycol lubricant. Tests were conducted to determine the cooling time required to decrease the temperature of evaporator water from 25 °C to 4 °C, coefficient of performance, and exergy losses in the system components. They showed that lubricant containing 0.2% gold NPs and 0.005% CNT, could perform at a cooling time of about 1600 s while an 8% reduction in exergy loss was achieved for the case of doping with 0.1% of gold NPs and 0.005% CNT, in comparison to R134a refrigerant.

Krishnan *et al*. (2018) studied the feasibility of using nanolubricants in vapor compression refrigeration systems, using NPs of Al_2O_3, SiO_2, zirconium dioxide (ZrO_2), and CNT, dispersed in synthetic lubricating oil based on polyolester (POE), and R134a refrigerant. Through an analysis of the thermophysical properties and evaluation of the coefficient of performance of the system, it was observed that the addition of SiO_2 NPs is the most viable, with a maximum increase of 21.83% of the COP for a 0.1% configuration of SiO_2 in 200 ml POE.

Harichandran *et al*. (2019) carried out an analysis with the purpose of investigating the effect of different volume concentrations of hexagonal boron nitride (h-BN) in the polyester oil-based lubricant. They aimed to observe the behavior of the density, viscosity, and tribological aspects and to evaluate the performance coefficient of a vapor compression refrigeration system using R134a refrigerant. The choice of h-BN is justified due to its lubrication, thermal conductivity, and chemically inert properties. The analysis was carried out on a test bench by dispersing 0.1%, 0.2%, 0.3%, and 0.4% of h-BN in polyester oil. A reduction in friction force was identified thanks to the addition of nanolubricant, proving that the addition of h-BN NPs could decrease the friction coefficient and the wear rate, maintaining a layer of lubricating film on the components. It was found that at the concentration of 0.3%, h-BN increases the cooling capacity by about 34% and reduces the compression work by approximately 16%, generating a 60% increase in the COP of the system.

Besides the use of metallic NPs as mentioned above, the carbon compounds have also attracted a large amount of for the application of nanotechnology in refrigeration systems. In the work carried out by Babarinde *et al*. (2020), graphene NPs with concentrations of 0.2 g/L, 0.4 g/L, and 0.6 g/L were dispersed in mineral oil and tested in a domestic refrigerator using different loads of R600a. A reduction in system energy consumption and an increase in the COP were observed at a concentration of 0.2 g/L, while a maximum COP of 3.2, and energy consumption of 0.0651 kW were achieved for 60 g of refrigerant. Yang *et al*. (2020) have also studied the effect of graphene nanosheets on the performance of a domestic refrigeration system where three different concentrations of graphene were dispersed in mineral oil. Among the results found was a reduction in the average compressor discharge temperature of 2.5%, 3.8% 4.6% compared to the system without the use of nanolubricant, and a reduction of about 14.8%, 18.5%, and 20.4% in energy consumption of the refrigeration system at the concentrations of 10 mg/L, 20 mg/L, and 30 mg/L of graphene nanosheets dispersed in lubricating oil, respectively.

Soliman, Rahman and Ookawara (2019) carried out a study on the effect of Al_2O_3 NPs on the performance of a vapor compression cycle. For this study, four cases were analyzed: the reciprocating compressor filled with POE mineral oil without NPs and with concentrations of 0.05%, 0.1%, and 0.15% of Al_2O_3 NPs dispersed in mineral oil. Such strategy results in a 10% increase in actual maximum COP and a 9.28% reduction in system energy consumption for 0.1% Al_2O_3 concentration.

Nair, Parekh and Tailor (2020) experimentally investigated the use of NPs dispersed in PAG (polyalkylene glycol) synthetic lubricating oil in a refrigeration system. In this work, Al_2O_3 NPs were also used, as they have superior thermophysical properties compared to other NPs such as CuO and TiO_2. Using the R134a refrigerant fluid, a cooling capacity of 3.99 kW was observed with the use of Al_2O_3 NPs compared to that of pure PAG oil, which presented a value of 3.78 kW, showing a significant increase in the cooling capacity of the system. A maximum reduction of 6.1% in compressor power per unit of cooling capacity was found with the use of nanolubricant compared to pure PAG oil, in addition to an increase in COP of 6.5%. Through the pull-down test, it was revealed that there was a 170 s reduction in the compressor operating time when using a mixture of PAG oil and Al_2O_3 NPs.

The experimental work by Adelekan *et al*. (2019a) investigated the performance behavior of a domestic refrigeration system with the addition of TiO_2 NPs. For this study, LPG gas and TiO_2 concentrations ranging from 0.2 g/L to 0.6 g/L were used as refrigerants. Among the parameters studied were: system energy consumption, cooling capacity, COP, and thermal conductivity at compressor discharge. As a main result, they observed an increase in the COP of the system, with average values of 3.13, 3.55, 5.36, and 3.92 for the pure lubricant with concentrations of 0.2 g/L, 0.4 g/L, and 0.6 g/L of TiO_2, respectively.

Table 1 presents a compilation of the data discussed above, listing some of the main contributions generated by NPs in vapor compression refrigeration systems. The main configurations used in the works are presented, such as refrigerant fluid, NPs type, and their concentrations in the base fluid.

Table 1 ▼
Results of the effect of nanoparticles in vapor compression refrigeration systems.
Source: research data

Authors	Refrigerant	Nanoparticles	Nanoparticles concentration	Results
Manikanden and Avinash (2019)	R290	CuO/CuO doped with Ag	1.0%	15% to 28% energy consumption reduction.
Kumar and Singh (2017)	R290/R600a	ZnO	0.2% to 1.0%	3.40% to 7.48% energy consumption reduction plus 46% COP increase.
Jatinder *et al.* (2019)	R600a	TiO_2	0.2 g/L, 0.4 g/L and 0.6 g/L	1.94% to 33.3% energy consumption reduction.
Senthilkumar *et al.* (2021)	R600a	ZnO/SiO_2	0.4 g/L and 0.6 g/L	78 W minimum work in the compressor and 42% COP increase.
Yang *et al.* (2020)	R600a	Graphene	10 mg/L, 20 mg/L and 30 mg/L	14.8%, 18.5% and 20.4% energy consumption reduction.
Mohan *et al.* (2020)	R134a	Au, CNT e $HAuCl_4$	0.005%, 0.1% and 0.2%	31.7% COP increase by having 0.1% Au + 0.005% CNT.
Adelekan *et al.* (2019b)	R600a	TiO_2	0.1 g/L, 0.3 g/L and 0.5 g/L	Maximum COP of 4.99.
Krishnan *et al.* (2018)	R134a	Al_2O_3, SiO_2, ZrO_2 e CNT	0.1%, 0.2% and 0.3%	21.83% COP increase with 0.1% SiO_2.
Harichandran *et al.* (2019)	R134a	h-BN	0.1% to 0.4%	16% reduction of compressor work with 0.3% h-BN concentration.
Babarinde *et al.* (2020)	R600a	Graphene	0.2 g/L, 0.4 g/L and 0.6 g/L	Maximum COP of 3.2 with 0.2 g/L graphene concentration.
Nair, Parekh and Tailor (2020)	R134a	Al_2O_3	0.5%	6.4% refrigeration capacity increase + 6.5% COP increase.
Adelekan *et al.* (2019a)	GLP	TiO_2	0.2 g/L, 0.4 g/L and 0.6 g/L	41% COP increase with 0.4 g/L of TiO_2.
Soliman, Rahman and Ookawara (2019)	R143a	Al_2O_3	0.05%, 0.1% and 0.15%	10% COP increase and 9.28% energy consumption reduction.

By and large, it could be observed that the use of nanolubricants or nanorefrigerants in vapor compression refrigeration systems is a promising strategy to improve the performance of the evaluated systems. This fact is evidenced by the increase in COP and cooling capacity, which presents higher values with the addition of nanoparticles. It was also found that reducing energy consumption is one of the main advantages of using nanofluids. In Table 1, it is possible to observe through the work of Manikanden and Avinash (2019) a reduction of up to 28% in energy consumption with the use of Ag-doped CuO NPs. It is worthy to mention that the concentration of NPs is a determining factor in the performance of the system, as the work presented by Soliman, Rahman and Ookawara (2019) demonstrated that the maximum increase in COP and the lowest energy consumption occurred with the use of 0.1% of Al_2O_3 NPs.

In addition to the concentration and type of NPs, the type of refrigerant also has a direct influence on the performance of vapor compression systems. The work by Adelekan *et al*. (2019a) showed that for a concentration of 0.4 g/L of TiO_2 and LPG-based refrigerant, a COP of 5.36 was obtained. In this same work, the author demonstrated that a maximum COP of a 4.99 could be achieved using R600a refrigerant and TiO_2 having a concentration of 0.1 g/L.

After analyzing the presented works in literature, it was found that the use of NPs in refrigeration systems significantly reduces the energy consumption of the compressor, in addition to promoting an improvement in the cooling capacity of the system. These changes provide an increase in the system's performance coefficient, reducing its operating cost. It is possible to highlight that addition of the NPs to the lubricating fluid reduced the effects generated by friction on the compressor components. This phenomenon is observed due to the improvement of the tribological properties of the lubricating fluid with the addition of solid particles on a nanometric scale, facilitating the creation of lubricating layers on the internal surfaces of the compressor, reducing friction dissipating forces, the work of the compressor, and its temperature. In addition to the improvement in system performance, it is possible to observe a dependence of thermophysical and tribological properties on the concentration of NPs dispersed in the base fluid and on the type of NP used in the experiment.

4 Final considerations

It was concluded that the research objective was completely achieved since the purpose of this systematic literature review was to evaluate the influence of the use of NPs in vapor compression refrigeration systems on their energy performance, from the in-depth research of relevant scientific published articles in recent years. These results could be useful to provoke and motivate other studies related to increased energy efficiency and improved mechanical performance in refrigeration systems through the use of nanotechnology.

Although the use of nanofluids presents a reduction in the energy consumption of vapor compression refrigeration systems, it is necessary to carry out more studies on the effects of prolonged use of this type of technology. Determining the ideal concentration of NPs that should be used for each system and evaluating the cost involved in the preparation of the materials are still among the important challenges of these studies for the advancements and mass applications of them.

This work is part of a larger project that is being developed by the Interdisciplinary Research Group on Thermal Engineering and Materials Engineering at the Federal Rural University of Pernambuco (UFRPE). The results presented will serve as a basis for future work within the research group that already works on solutions to increase energy efficiency, to increase mechanical performance, and to reduce environmental impacts in refrigeration systems based on exergoeconomic, exergoenvironmental diagnosis, development of new materials, and cycle analysis. Experiments with the application of NPs in the compressor's lubricating oil and in the refrigerant for different operating conditions will be carried out on the didactic workbench of vapor compression refrigeration of this research group.

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Conflict of interest

The authors declare no conflict of interest.

References

ADELEKAN, D. S.; OHUNAKIN, O. S.; GILL, J.; ATAYERO, A. A.; DIARRA, C. D.; ASUZU, E. A. Experimental performance of a safe charge of LPG refrigerant enhanced with varying concentrations of TiO_2 nano-lubricant in a domestic refrigerator. **Journal of Thermal Analysis and Calorimetry**, v. 136, n. 6, p. 2439-2448, 2019a. DOI: https://doi.org/10.1007/s10973-018-7879-2.

ADELEKAN, D. S.; OHUNAKIN, O. S.; GILL, J.; ATIBA, O. E.; OKOKPUJIE, I. P.; ATAYERO, A. A. Experimental investigation of a vapour compression refrigeration system with 15nm TiO_2-R600a nano-refrigerant as the working fluid. **Procedia Manufacturing**, v. 35, p. 1222-1227, 2019b. DOI: https://doi.org/10.1016/j.promfg.2019.06.079.

BABARINDE, T. O.; AKINLABI, S. A.; MADYIRA, D. M.; EKUNDAYO, F. M. Enhancing the energy efficiency of vapour compression refrigerator system using R600a with graphene nanolubricant. **Energy Reports**, v. 6, suppl. 2, p. 1-10, 2020. DOI: https://doi.org/10.1016/j.egyr.2019.11.031.

BABU, J. A. R.; KUMAR, K. K.; RAO, S. S. State-of-art review on hybrid nanofluids. **Renewable and Sustainable Energy Reviews**, v. 77, p. 551-565, 2017. DOI: https://doi.org/10.1016/j.rser.2017.04.040.

BRASIL. Ministerio de Minas e Energia. **Boletim mensal de monitoramento do Sistema Elétrico Brasileiro**: Fevereiro/2021. Brasília, DF: Ministério de Minas e Energia, 2021. Available at: https://www.gov.br/mme/pt-br/assuntos/secretarias/energia-eletrica/publicacoes/boletim-de-monitoramento-do-sistema-eletrico/2021/02-boletim-de-monitoramento-do-sistema-eletrico-fev-2021.pdf. Accessed on: 19 may 2021. In Portuguese.

CARDOSO, R. B. Impactos da lei de eficiência energética 10.295/2001, em equipamentos elétricos e a gás. **Research, Society and Development**, v. 4, n. 2, p. 116-124, 2017. DOI: https://doi.org/10.17648/rsd-v4i2.73. In Portuguese.

CHOI, S. U. S; EASTMAN, J. A. **Enhancing thermal conductivity of fluids with nanoparticles**. Argonne: Argonne National Lab, 1995. Available at: https://www.osti.gov/biblio/196525. Accessed on: 24 may 2021.

FONSECA, L. F. S.; SILVA JÚNIOR, J. M.; FARIAS NETO, J. R.; ABRAHÃO, R.; CARVALHO, M. Vulnerabilidade das regiões semiáridas às mudanças climáticas: impactos na produção de energia fotovoltaica. **Research, Society and Development**, v. 10, n. 3, e4010312931, 2021. DOI: http://dx.doi.org/10.33448/rsd-v10i3.12931. In Portuguese.

HARICHANDRAN, R.; PAULRAJ, P.; RAJA, S. M. P.; RAMAN, J. K. Effect of h-BN solid nanolubricant on the performance of R134a–polyolester oil-based vapour compression refrigeration system. **Journal of the Brazilian Society of Mechanical Sciences and Engineering**, v. 41, n. 3, 140, 2019. DOI: https://doi.org/10.1007/s40430-019-1645-7.

JATINDER, G; OHUNAKIN, O. S.; ADELEKAN, D. S.; ATIBA, O. E.; DANIEL, A. B.; SINGH, J.; ATAYERO, A. A. Performance of a domestic refrigerator using selected hydrocarbon working fluids and TiO_2–MO nanolubricant. **Applied Thermal Engineering**, v. 160, 114004, 2019. DOI: https://doi.org/10.1016/j.applthermaleng.2019.114004.

KRISHNAN, R. S.; ARULPRAKASAJOTHI, M.; LOGESH, K.; RAJA, N. D.; RAJENDRA, M. Analysis and feasibilty of nano-lubricant in vapour compression refrigeration system. **Materials Today: Proceedings**, v. 5, n. 9, part 3, p. 20580-20587, 2018. DOI: https://doi.org/10.1016/j.matpr.2018.06.437.

KUMAR, R.; SINGH, J. 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 and Mass Transfer**, v. 53, n. 5, p. 1579-1587, 2017. DOI: https://doi.org/10.1007/s00231-016-1921-3.

LEE, K.; HWANG, Y.; CHEONG, S.; KWON, L.; KIM, S.; LEE, J. Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil. **Current Applied Physics**, v. 9, n. 2 suppl., p. e128-e131, 2009. DOI: https://doi.org/10.1016/j.cap.2008.12.054.

MANIKANDEN, V. S.; AVINASH, A. An experimental insight into the effects of silver-doped cupric oxide nanoparticles on the performance of hydrocarbon refrigeration system. **SN Applied Sciences**, v. 1, n. 11, 1462, 2019. DOI: https://doi.org/10.1007/s42452-019-1528-7.

MARQUES, A. S.; CARVALHO, M.; OCHOA, A. A. V.; SOUZA, R. J.; SANTOS, C. A. C. Exergoeconomic assessment of a compact electricity-cooling cogeneration unit. **Energies**, v. 13, n. 20, 5417, 2020. DOI: https://doi.org/10.3390/en13205417.

MOHAN, K.; SUNDARARAJ, S.; KANNAN, K. G.; KANNAN, A. Experimental analysis on refrigeration system using CNT, gold & HAUCL4 nano fluids. **Materials Today: Proceedings**, v. 33, part 1, p. 360-366, 2020. DOI: https://doi.org/10.1016/j.matpr.2020.04.156.

NAIR, V.; PAREKH, A. D.; TAILOR, P. R. Experimental investigation of a vapour compression refrigeration system using R134a/nano-oil mixture. **International**

Journal of Refrigeration, v. 112, p. 21-36, 2020. DOI: https://doi.org/10.1016/j.ijrefrig.2019.12.009.

OLIVEIRA, A. M.; GONÇALVES, L. M.; MESQUITA, A. Z.; BANDARRA FILHO, E. P.; FERREIRA, A. G. Desempenho termo-hidráulico de nanofluidos compostos por nanotubos de carbono de paredes múltiplas funcionalizados (MWCNT-OH/água). **Research, Society and Development**, v. 10, n. 3, e5910313031, 2021. DOI: http://dx.doi.org/10.33448/rsd-v10i3.13031. In Portuguese.

PAGANI, R. N.; KOVALESKI, J. L.; RESENDE, L. M. Methodi ordinatio: a proposed methodology to select and rank relevant scientific papers encompassing the impact factor, number of citation, and year of publication. **Scientometrics**, v. 105, n. 3, p. 2109-2135, 2015. DOI: https://doi.org/10.1007/s11192-015-1744-x.

SENTHILKUMAR, A.; ANDERSON, A.; PRAVEEN, R. Prospective of nanolubricants and nano refrigerants on energy saving in vapour compression refrigeration system: a review. **Materials Today: Proceedings**, v. 33, part 1, p. 886-889, 2020. DOI: https://doi.org/10.1016/j.matpr.2020.06.416.

SENTHILKUMAR, A.; SAHALUDDEEN, P. A. M.; NOUSHAD, M. N.; MUSTHAFA, E. K M. Experimental investigation of ZnO / Sio_2 hybrid nano-lubricant in R600a vapour compression refrigeration system. **Materials Today: Proceedings**, v. 45, part 7, p. 6087-6093, 2021. DOI: https://doi.org/10.1016/j.matpr.2020.10.180.

SHARIF, M. Z.; AZMI, W. H.; MAMAT, R.; SHAIFUL, A. I. M. Mechanism for improvement in refrigeration system performance by using nanorefrigerants and nanolubricants: a review. **International Communications in Heat and Mass Transfer**, v. 92, p. 56-63, 2018. DOI: https://doi.org/10.1016/j.icheatmasstransfer.2018.02.012.

SOLIMAN, A. M. A.; RAHMAN, A. K. A.; OOKAWARA, S. Enhancement of vapor compression cycle performance using nanofluids: experimental results. **Journal of Thermal Analysis and Calorimetry**, v. 135, n. 2, p. 1507-1520, 2019. DOI: https://doi.org/10.1007/s10973-018-7623-y.

SOUZA, R. J.; SANTOS, C. A. C.; OCHOA, A. A. V.; MARQUES, A. S.; M. NETO, J. L.; MICHIMA, P. S. A. Proposal and 3E (energy, exergy, and exergoeconomic) assessment of a cogeneration system using an organic Rankine cycle and an absorption refrigeration system in the Northeast Brazil: thermodynamic investigation of a facility case study. **Energy Conversion and Management**, v. 217, 113002, 2020. DOI: https://doi.org/10.1016/j.enconman.2020.113002.

YANG, S.; CUI, X.; ZHOU, Y.; CHEN, C. Study on the effect of graphene nanosheets refrigerant oil on domestic refrigerator performance. **International Journal of Refrigeration**, v. 110, p. 187-195, 2020. DOI: https://doi.org/10.1016/j.ijrefrig.2019.11.008.