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An Overview of Techniques for Enhancing the Performance of Refrigeration Systems

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Abstract

Enhancing the efficiency of refrigeration and air conditioning systems contributes to more energy-efficient buildings and yields significant environmental benefits. Technological innovation has been a key driver in improving the performance of refrigeration systems. This article reviews tested strategies for optimising the performance of air conditioning and refrigeration systems, which remain among the most energy-intensive end uses in both residential and non-residential buildings. It reveals that the search for alternatives to ozone-depleting and high-global-warming refrigerants during this transitional period should focus not only on environmentally friendly refrigerants but also on those that are energy-efficient and possess a higher coefficient of performance than the refrigerants they replace. In addition, the potential benefits of retrofitting should be examined as a means of improving system performance. While the installation of new systems may be required to achieve superior environmental control and energy performance, such an approach often entails a high initial cost. Nevertheless, it may ultimately prove to be the most cost-effective solution over the equipment's lifespan. This article explores two prominent applications of nanotechnology that can enhance heat transfer in refrigeration systems. Other cutting-edge technologies, such as the use of ejectors, internal heat exchangers, and cascade systems are discussed for their capacity to significantly improve system performance. Overall, this work offers a comprehensive assessment of viable methods for enhancing the performance of air conditioning and refrigeration equipment, providing valuable insights for researchers in the field.

Keywords

Energy consumption, energy efficiency, nanorefrigerant, performance enhancement, refrigeration system

1 Introduction

Energy is fundamental to the growth and survival of all living beings and plays a pivotal role in a country's socioeconomic progress and overall wellbeing.[1] However, the energy systems are now facing significant challenges, including excessive consumption, insufficient supply, and environmental issues such as air pollution, ozone depletion, global warming, and climate change. As such, energy remains an unparalleled resource that presents ongoing challenges to humanity.[2]

Maintaining a desired temperature for heating and cooling is considered one of the most significant technological achievements of our time.[3] Heating, ventilation, and air conditioning (HVAC) systems have become indispensable, not only for residential and workplace comfort but also for industrial operations. Enhancing these systems can lead to more energy-efficient buildings and beneficial effects on the environment. Energy efficiency plays a critical role in the ability of high-performance systems to mitigate climate change.[4] Refrigeration, in particular, is crucial for achieving the UN Sustainable Development Goals by addressing challenges such as disease, hunger, and poverty while promoting access to quality education, nutritious food, and healthcare. The demand for HVAC systems has increased due to population growth, economic expansion, and rising average global temperatures.[5]

Technological innovation has been a driving force behind enhancements in refrigeration system performance. Tackling energy concerns requires the development of advanced technologies that maximise efficiency while minimising adverse ecological implications.[6] Reducing energy consumption in HVAC systems cannot be achieved through a single measure, such as selecting an efficient refrigerant, but rather through an integrated approach that leverages all available opportunities. The operational efficiency of refrigeration and air conditioning systems is determined by the thermodynamic parameters of the refrigerant, liquid loss, heat exchange efficiency, system design, and the materials used in system components. Several studies have explored strategies to improve the performance of air conditioning and refrigeration systems. These include replacing traditional refrigerants with innovative alternatives, employing nanolubricants and nanorefrigerants to enhance heat transmission, reducing heat loads, and optimising system design for improved performance.[7,8] However, this article provides an in-depth review of effective methods to enhance the energy performance of refrigeration and air conditioning systems, aiming to reduce their indirect contributions to global warming.

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2 Refrigeration systems and residential energy consumption

Air conditioning and refrigeration systems are currently the most significant energy consumers in residential and non-residential buildings. Both developed and developing nations have seen a noticeable increase in the energy consumption of these systems. In the United States, HVAC systems account for over fifty percent of household energy use. Fig. 1 illustrates that refrigeration, air conditioning, and space heating account for roughly 54 % of home energy consumption. Additionally, in many affluent nations, the residential sector accounts for about 21 % of overall energy consumption. The percentage of each sector's total energy use in 2017 is displayed in Fig. 2.[9,10] Nonetheless, *Oyedepo*[11] reports that in developing nations like Nigeria, the residential sector consumes around 65 % of all energy (Fig. 3).

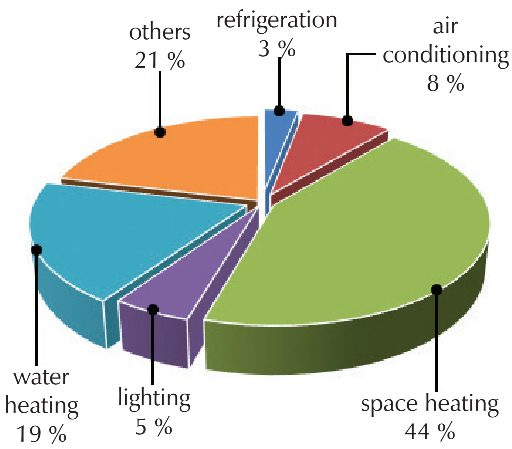

Fig. 1 – Distribution of home energy consumption[9]

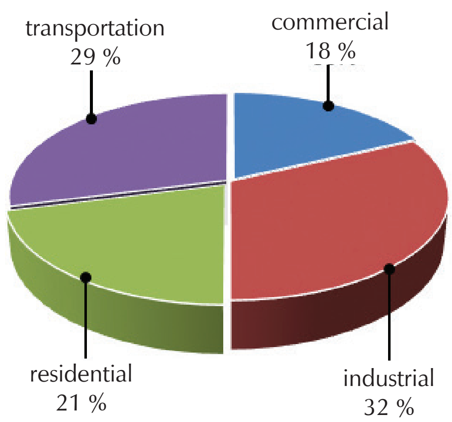

Fig. 2 – Percentage of total energy consumption by sector in the US[10]

Refrigeration equipment serves a wide range of purposes, from small-scale applications such as food processing and air conditioning in homes, vehicles, and workplaces to large-scale industrial and commercial operations. It plays a critical role in reducing food waste through the cold chain. The use of air conditioning and refrigeration systems has increased due to population growth, industrialisation, and technological advancements, resulting in increased energy consumption. As the use of refrigeration systems grows, improving their efficiency becomes essential to curbing rising electricity consumption. Low-performance refrigeration systems consume more energy per tonne of refrigeration and generate higher carbon footprints, which negatively impact both society and the environment.[12] Consequently, superior cooling performance, energy efficiency, and environmental safety have now become key principles in the design and operation of refrigeration systems.

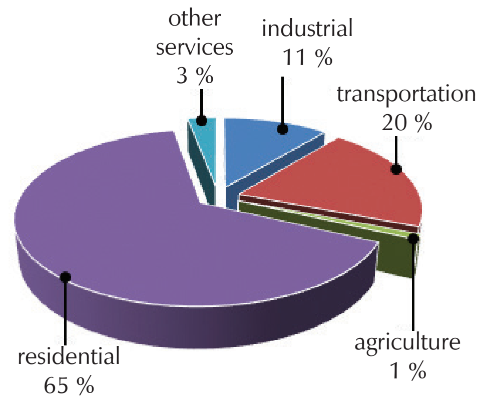

Fig. 3 – Percentage of total energy consumption by sector in Nigeria[11]

2.1 Opportunities for energy improvement in the refrigeration sector

Achieving future sustainability relies heavily on more efficient energy use. Areas of opportunity to improve energy efficiency in the refrigeration sector span various applications: Food processing, delivery, and preservation (cold supply chain) as shown in Fig. 4; Liquefaction and extraction of gases in the oil and gas industry (liquefaction cold box) as shown in Fig. 5; Heat removal in chemical reactions, critical for chemical industries; Cold processing of metals in high-precision manufacturing; and Energy-efficient storage of blood plasma, medicines, and vaccines.[13]

The energy efficiency of refrigeration systems is measured by the ratio of cooling capacity to energy input, known as the coefficient of performance. Enhancing energy efficiency requires advancements in technology or system design improvements that achieve less energy input or consumption for the same performance or cooling capacity.[14]

A cold supply chain, illustrated in Fig. 4, is a supply chain and network of facilities regulated by temperature control. Its operations are designed to ensure items remain consistently cold throughout distribution. This system maintains products, such as medicines or fresh food at precise low temperatures during their journey from production to preservation, and delivery to the end customer. By preventing exposure to heat, it safeguards product integrity and usability, reducing the risk of deterioration or dam-

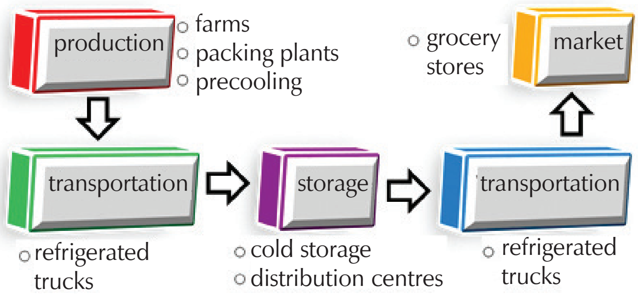

Fig. 4 – Cold supply chain

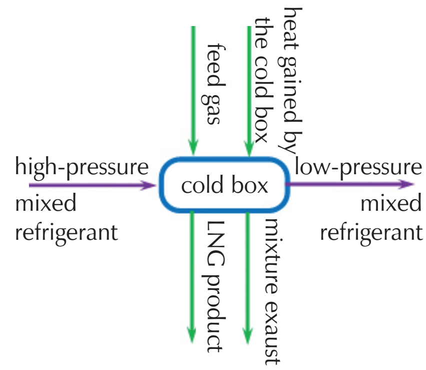

Fig. 5 – Liquefaction cold box[13]

age. To enhance energy efficiency and reduce energy consumption during distribution, several techniques must be employed. Refrigeration equipment should be optimised with variable-speed compressors, advanced control systems, and enhanced insulation to minimise heat loss. Maintaining stable temperatures throughout the cold chain requires continuous monitoring and adjustment based on product-specific requirements, as well as reducing unnecessary chilling cycles. Fig. 5 illustrates a liquefaction cold box, a cylindrical structure that houses freezing devices, pipelines, and equipment for liquefying and purifying natural gas. The heat exchanger and pipes are insulated with perlite to keep them cool. Improving energy efficiency within the liquefaction process involves optimising the amount of cold energy generated per unit of energy input by minimising heat leakage and reducing energy waste throughout the process.

2.2 Power consumption and the equivalent CO_2 emissions of a household refrigerator

The average power consumption of a domestic refrigerator ranges from 400 to 800 W, with a grid-connected 100-litre refrigerator averaging 600 W.[15] However, because the appliance cycles on and off throughout the day, its actual power usage is significantly lower than the stated wattage. As a general rule of thumb, 50 % of the stated power indicates that the operational wattage of the appliance would be 300 (0.3 kWh). Based on this, the daily, monthly, and yearly power consumption of a single refrigerator would be 7.2, 216.0, and 2628.0 kWh, respectively (Table 1). The exact electricity consumption depends on factors such as the refrigerator's age, make, and model. The corresponding CO_2 emissions per kWh of electricity vary depending on how the electricity is generated. Reported data suggest that CO_2 emissions average around 200 g *per* kWh for cleaner energy sources, 1000 g *per* kWh for highly polluting sources, and approximately 500 g *per* kWh in Nigeria.[16] This means that each unit of electricity generated in Nigeria emits around 0.5 kg of CO_2. Fig. 1 shows the comparable CO_2 emissions associated with operating a single refrigerator.

Table 1 – Electricity usage of a refrigerator with average running wattage of 300 *per* hour

Refrigerator operating period / days	Electricity used / kWh	Equivalent CO_2 emission / kg CO_2
1	7.2	3.6
7	50.4	25.2
30	216.0	108.0
365	2628.0	1314.0

3 Refrigerant substitution

One of the key benefits of phasing out environmentally harmful refrigerants, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in refrigeration systems, is the opportunity to adopt energy-efficient refrigerants that are ecologically harmless and can be used as alternative working fluids in various vapour compression refrigeration systems. A number of companies have taken advantage of the opportunity to alter their systems in order to enhance energy efficiency in new refrigeration equipment.[15] Recently developed refrigerants must not only be environmentally benign but also contribute to lower power consumption of the system. Consequently, energy efficiency must be considered in the phase-down of hydrofluorocarbons (HFCs), which have a high global warming potential (GWP). This approach aims to reduce consumers' electricity bills and minimise carbon dioxide

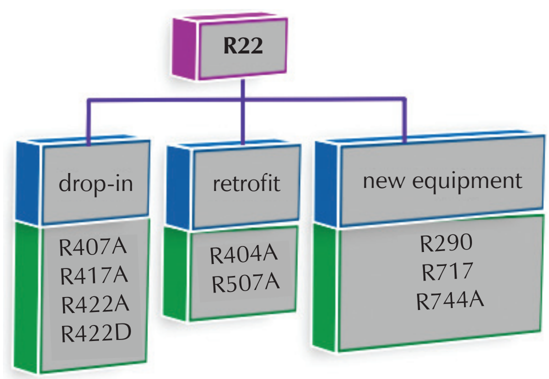

Fig. 6 – R22 replacement options

emissions from power generation. According to *Hmood et al*.[17], drop-in replacement, retrofitting with new refrigerants, and fresh system installation are the three basic refrigerant substitution methods. The options available for replacing R22 refrigerant, which is being gradually phased out are shown in Fig. 6.

3.1 Drop-in replacement of refrigerants

A drop-in refrigerant is one that possesses comparable properties to the original refrigerant. This type of replacement is straightforward and eliminates the need for modifications or upgrades to the components of the refrigeration system. A drop-in replacement is suitable when there are no compatibility issues between the alternative refrigerant and the materials used in the existing refrigeration unit.[18] *Belman-Flores et al*.[19] analysed the energy and thermal performance of three low-GWP alternative cooling agents (R516A, R513A, and R1234ze) as drop-in replacements for R134a in a household refrigerator with a volume capacity of 513 l. The study employed the appropriate quantity charges for the three investigated refrigerants based on the unit's lowest energy usage. When compared to the baseline refrigerant (R134a), the findings revealed that R516A performed similarly as a drop-in replacement for R134a, while R1234ze showed a 13 % improvement in coefficient of performance (COP). Conversely, R513A demonstrated the largest decrease in COP, with approximately 28 % less efficiency than R134a.

Alba et al.[20] examined the effectiveness of four refrigerants as direct substitutes for R134a in refrigeration equipment using a molecular-based assessment technique. Their study linked molecular characteristics to achieved performance improvements, aiming to identify refrigerants that comply with environmental regulations while minimising climate impact. The model utilised was combined with technical parameters that allowed the search for suitability of presently used third-generation environmentally friendly operating fluids as drop-in substitute refrigerants. Performance parameters included COP, cooling capacity, and other thermophysical variables that have a direct influence on improving refrigeration system performance. The four drop-in working fluids (R1225ye, R1234ze, R1224yd, and R1123) demonstrated significant performance improvements compared to R134a.

Calleja-Anta et al.[21] conducted experiments in accordance with the EN 62552-2:2020 guideline to assess whether refrigerant blends could lower energy consumption in practical refrigeration units. Using a charge optimisation technique, they evaluated the effectiveness of five refrigerant blends (R600/R290, R600/R1234ze, and R600a/R1234yf) as drop-in replacements for R600a in a shopping mall refrigerator. The results indicated that three of the refrigerant blends improved the refrigerator's performance. This demonstrated that using refrigerant blends as direct substitutes for traditional working fluids in the system can reduce energy consumption and enhance refrigeration efficiency.

Elbel et al.[22] conducted research to identify an environmentally benign and more efficient refrigerant to replace R410A, which possesses a high GWP of 2088. The study evaluated the drop-in functionality of R32 (GWP of 675) in a chiller cooling unit initially intended for R410A. It employed season-dependent performance tests that focused on compressor output modulation approaches. The performances of the variable-speed and 2-stage compressors utilising R32 as a drop-in refrigerant were compared to systems that used R410A as the working fluid. The findings indicated that the two refrigerants performed similarly in the variable-speed compressor systems. However, R32 achieved better cooling capacity than R410A in the 2-stage compressor systems. This demonstrated how changing the cooling fluid may cause distinct variations in the functioning of a refrigeration system.

Kadhim et al.[23] theoretically evaluated three hydrofluoroolefin (HFO) cooling fluids as drop-in or direct substitutes for R134a in a home refrigeration unit. The study aimed to aid the removal of the high-GWP refrigerants from refrigeration systems. The standard working fluid in compact refrigerators (R134a) has a comparatively high GWP of 1430, whereas HFOs are environmentally benign refrigerants with GWPs of less than 6. REFPROP software was used to evaluate the performance of the three HFOs (R1336mzz, R1234ze, and R1234yf) in a 200-L home refrigerator. The findings revealed that two of the three HFOs (R1234ze and R1234yf) provided superior cooling capacity and energy performance in terms of COP in the system compared to R134a.

3.2 Retrofitting replacement of refrigerants

Retrofitting refers to the process of adapting existing refrigeration systems to meet environmental control criteria. This involves modifying systems that are utilising phased-out refrigerants to function effectively with new sustainable and energy-efficient refrigerants throughout their economic lifespan.[14] It aids in updating facilities to meet the requirements of operating in a modern setting. The consequences of retrofitting a system vary depending on the components and refrigerant used. In certain instances, it might be a simple operation requiring the replacement of expansion valves, while in others, it might require an elaborate procedure including oil changes, system purging, or component replacement. Retrofitting is sometimes necessary due to the reduced availability of phased-out refrigerants under environmental regulations or as a means to implement new refrigerants that improve energy performance.

In order to improve the energy performance of a refrigeration system, *Banjo et al*.[24] assessed the operating parameters of a retrofitted refrigerator. The study experimentally employed isobutane refrigerant (R600a) as a replacement for R134a. Their study assessed parameters such as thermal performance in terms of cooling load, COP, and power consumption for both the retrofit and initial refrigerant. The results revealed that R600a outperformed R134a in all parameters, making it a highly efficient retrofit refrigerant.

Thavamani and *Senthil*[25] conducted an experimental study on a home refrigerator retrofitted with a blend of 51 % butane and 49 % propane as a replacement for R134a. Due to its much lower density, the refrigerant mixture required a smaller charge than R134a. The refrigerant control used a 3.75 m capillary tube to deliver the necessary pressure decrease. Energy efficiency tests and pull-down performance assessments were carried out using the hydrocarbon mixture and compared to baseline testing using R134a. The retrofitted unit demonstrated a 40 % improvement in COP and a 17.86 % reduction in daily energy consumption.

Bolaji et al.[26] retrofitted a domestic refrigerator with R152a instead of the standard refrigerant (R134a). R152a is utilised as a retrofit refrigerant due to its low GWP of 124 when compared to R134a, which has a value of 1430. The results revealed a close match in the thermophysical parameters of the two refrigerants. The retrofitted unit used significantly less energy, and its cooling capacity increased by 14.6 %, while the average COP increased by 12.2 % when compared to the baseline test. However, R152a is a moderately flammable fluid. The research advocated for its use as a retrofit substitute for R134a in existing cooling systems owing to its superior energy efficiency as a global warming mitigation method. To avoid potential fire risks of R152a, its use should be limited to refrigerators with minimal refrigerant charge.

Oruc et al.[27] experimentally evaluated the performance of low-GWP refrigerant (R452A) as a retrofit for R404A. The tests were conducted at three regulated condenser temperatures (55, 40, and 35 °C), and three evaporation temperatures (3, 0, and −3 °C). The results revealed that retrofitting the system significantly improved its performance. R452A demonstrated higher energy efficiency throughout all test set conditions. R452A also performed more efficiently in terms of cooling capacity and COP at higher condenser temperatures (55 and 40 °C).

3.3 Characteristics and potential issues with new refrigerants

Alternative refrigerants are typically characterised by their low environmental impact, featuring a low GWP, zero ozone depletion potential (ODP), and non-toxic properties. They exhibit high heat transfer efficiency, maintaining good thermodynamic properties suitable for refrigeration applications, and compatibility with existing refrigeration systems depending on the specific application. They are often non-flammable, and have appropriate operating pressures. However, some new refrigerants may pose challenges such as flammability (*e.g.*, hydrocarbons), high operating pressures in some cases (*e.g.*, carbon dioxide), or toxicity (*e.g.*, ammonia), requiring specialised infrastructure for safe handling.

Achieving an ideal refrigerant with all desired properties remains challenging. However, when selecting new refrigerants, it is crucial to select refrigerants that can maintain a direct and indirect environmental balance, safety and product sustainability considering all the design and technological options. Some alternative refrigerants are more efficient for air conditioning while others are more efficient for refrigeration. The main challenge of hydrocarbon refrigerants is flammability. Refrigerants are classified by flammability risks: A1 – no flame propagation; A2 – lower flammability; and A3 – higher flammability. Hydrocarbons, for instance, fall under the A3 category and are typically restricted to small refrigeration systems with lower quantity charges.[26]

Hydrofluoroolefins (HFOs), classified as A2L refrigerants, are mildly flammable with low flame velocity and are less easily ignited. They tend to burn slowly and give off little heat.[23] While CO_2 is not combustible like hydrocarbons, it operates at pressures almost twice the typical pressure level in a modern air conditioning system,[14] thus necessitating the use of specialised components such as gas-coolers to ensure reliable operation of the system. Ammonia, known for its excellent heat transfer and pressure drop properties that improve system performance, poses safety concerns due to its flammability and toxicity, requiring specific equipment to prevent accidents.

3.4 New system installation

Some refrigerants are not suitable for retrofitting existing fluorocarbon refrigerant systems without substantial redesigns to the existing equipment. In addition, certain refrigerants, particularly those with safety concerns, are only recommended for use in systems specifically designed for them. New installations may be necessary to fulfil environmental control requirements and enhance the energy performance of refrigeration systems. Although this option may incur the highest initial cost, it could prove the most cost-effective over the equipment's lifetime. *Saengsikhiao* and *Taweekun*[28] conducted an installation in supermarket cold rooms to improve energy efficiency. These cold rooms were operational 18 hours a day using newly installed semi-hermetic compressors. The study modified the materials used for refrigeration cabinets, doors, and frames to lower the cooling load and reduce stress on the compressor. The experiments were performed at superheat, condenser, and evaporator temperatures of 10, 38, and −10 °C, respectively. The findings demonstrated that the new installations reduced the amount of energy required by the cold rooms by up to 50 %. The return on investment was estimated at fourteen months.

To enhance the energy efficiency of residential refrigeration units, *Dogan et al*.[29] replaced the conventional finned-tube condenser with a novel condenser made of a flat-tube channel finned with inset strips. The newly installed condenser was evaluated using three distinct capillary tube lengths and refrigerant loads. The results indicated that the system with the new condenser outperformed the previous system, requiring a 10.7 % lower refrigerant charge. Furthermore, the daily energy consumption of the new system decreased by 5.7 % compared to the baseline system under identical operating conditions.

Yang et al.[30] explored improving the efficiency of a residential refrigerator by incorporating a newly designed flying-wing evaporator in place of the system's standard plate-on-tube evaporator. The tubes of the newly installed evaporator exhibited good thermal contact with the fins, significantly enhancing heat transfer efficiency. The study compared different configurations of the novel evaporator with baseline tests using a traditional evaporator in a household refrigerator. The results revealed that the new evaporator improved performance, saving 4.28 % in energy, increasing cooling capacity by 9.3 %, and reducing refrigerant usage by 13.5 %.

Li et al.[31] evaluated the efficiency of a linear compressor as a replacement for a reciprocating compressor in a cooling unit, aiming to reduce the unit's energy consumption. The study developed a linear compressor and evaluated it under various operating conditions. The findings revealed that the refrigerator operated more efficiently with a linear compressor. The volumetric, isentropic, and motor efficiencies of the new installation improved significantly at the compressor motor frequency of 62.5 Hz. In addition, the linear compressor outperformed the reciprocating compressor in terms of COP and cooling capacity.

3.5 Economic viability of modifications and new installations

Performance analyses of modified refrigeration systems with new installations and existing systems are often conducted to evaluate the energy efficiency and cost viability of the newly installed systems. Modifications to refrigeration equipment in most reviewed studies resulted in significant reductions in energy consumption. Enhancing refrigeration efficiency is a primary concern in HVAC systems, as operating costs can exceed 50 % of a facility's total operating expenditures. The first stage in enhancing the efficiency of a refrigeration unit is to identify cost-saving opportunities while ensuring that any modifications result in reliable and effective operation. The cost of incorporating a component in an existing cooling unit can range from moderate for a small household unit to substantial for a complex commercial cooling system. However, retrofitting a pre-installed system typically costs considerably less, depending on the extent of the modifications and new installations. Furthermore, environmental standards such as EU F-gas restrictions must be observed.

4 Nanoparticles and their applications in refrigeration systems

Research is currently being conducted to develop cutting-edge technologies with the potential to significantly improve the quality of life worldwide. Over recent decades, nanotechnology and nanomaterials – emerging fields in science and engineering – have found applications across nearly every aspect of life. Remarkable progress has been observed globally, with nanotechnology increasingly being used to minimise pollution and develop more efficient energy systems. Nanomaterials have clearly demonstrated their value in the field of sustainable refrigeration and air conditioning systems. Their application has the potential to influence the energy consumption of the refrigeration industry.[32] Nanotechnology and nanomaterials can be employed in the refrigeration sector to decrease energy consumption. Nanotechnology has enormous benefits that the refrigeration sector can use to increase the efficiency and performance of air conditioning and refrigeration systems.

Nanotechnology is typically defined as reducing matter to a scale close to the atomic level to create novel materials, structures, systems, devices, and catalysts. At the nanoscale, many materials exhibit extraordinary biological, chemical, and physical features. Nanoscale materials are defined as substances with measurable dimensions less than 100 nm. One nanometre, commonly known as one-millionth of a millimetre, is equivalent to one-billionth of a metre. Nanomaterials possess exceptional electrical, magnetic, and optical characteristics. Due to their superior thermophysical characteristics and ability to alter the parameters of working fluids, the application of nanoparticles has attracted significant interest. Replacing traditional refrigerants with nanorefigerants in any refrigeration system can improve cooling capacity, reduce power consumption, and consequently enhance energy efficiency of the system. The two most common applications of nanotechnology in refrigeration systems are nanorefrigerants and nanolubricants. Incorporating nanoparticles into refrigerants or lubricants has been shown to significantly improve heat transfer in air conditioning, refrigeration, and other heat transfer systems.[33]

4.1 Application of nanolubricants for performance enhancement

Lubricant oil is essential in all vapour compression cooling systems for proper functioning and enhanced compressor performance. The dispersion of nanosized particles in the compressor oil used in the refrigeration system allows every drop of refrigerant to carry traces of nanoparticles during operation. Table 2 shows the effect of nanoparticle concentration in nanolubricants on the energy consumption of a refrigeration system.[34] *Pico et al*.[35] tested the performance of a vapour compressor-based refrigerator using refrigeration oil containing 0.1 and 0.5 % mass proportions of diamond nanoparticles and polyolester (POE) oil. Cooling capacity was assessed at various power input frequencies and evaporation temperatures. Introducing diamond nanoparticles to the cooling system increased cooling capacity and COP while also reducing compressor discharge temperatures. Cooling capacity improved by 4.2 % at low concentrations and 7.0 % at high concentrations of nanoparticles at lower compressor speeds compared to the poly-ol-ester oil system.

Choi et al.[36] investigated the impact of nanolubricants on compressor power input and heat transfer efficiency in the evaporator. The study used carbon nanotubes combined with base oil (POE) at a concentration of 0.1 % by mass of the nanoparticle to create the nanolubricant in a two-step process. The experiments were conducted on an R134a refrigeration system charged with the prepared nanolubricant. The results indicated an improvement in COP and a 17 % reduction in compressor power input.

Table 2 – Effect of nanolubricant on energy savings of a refrigeration system[34]

Mass ratio of nanoparticles in lubricant / %	Power consumption / kW	Power saving / %
0	0.113	0
0.2	0.112	0.79
0.4	0.110	3.37
0.6	0.107	5.55
0.8	0.105	7.31
1.0	0.105	7.31

The operating efficiency of three different concentrations of a hybrid nanolubricant (CuO/Al_2O_3) in a refrigeration unit using R600a as the working fluid was examined by *Senthilkumar et al*.[37] The tests used nanoparticle quantities of 0.6, 0.4, and 0.2 g l^{-1} in the oil. Both standard lubricants and nanolubricants were evaluated for their performance parameters, including power consumption, cooling effect, and COP. The findings indicated an improvement in the system's performance following the switch from traditional lubricant (mineral oil) to nanolubricant (CuO/Al_2O_3). The use of nanolubricant reduced power consumption by 24 %, while cooling capacity and COP increased by 20 and 27 %, respectively.

Shewale et al.[38] developed nano-oils to enhance the thermophysical properties and heat transfer capabilities of the compressor oil in a home air conditioner that used R134a as a working fluid. The produced nanolubricating oil was analysed using Labview software, and the findings showed a significant increase in both fluid density and thermal conductivity. The refrigerator's performance characteristics were experimentally evaluated using regular POE lubricant for the R134a system and nanolubricating oil (POE/TiO_2) as a substitute. The findings revealed that replacing conventional oil with a lubricant containing 0.2 % nanoparticles by volume resulted in an average improvement of 29 % in COP and a 27 % reduction in power consumption.

4.2 Application of nanorefrigerants for performance enhancement

Nanorefrigerants are specialised fluids that are made up of embedded nanoparticles in a base refrigerant. Adding nanoparticles to conventional refrigerants improves their heat transfer and thermophysical properties. *Kundan* and *Singh*[33] investigated the use of Al_2O_3-R134a nanorefrigerants to enhance heat transfer and performance of a refrigerator based on the vapour compression cycle. The experiments were conducted using nanorefrigerants with mass ratios of 0.5 and 1.0 % nanoparticles. The system's COP was measured by adjusting the flow rate of the nanorefrigerant. The findings revealed that using nanorefrigerant increased the system's COP by 7.20 and 16.34 % at flow rates of 0.0065 and 0.011 m^3 h^{-1}, respectively, compared to pure R134a as the operating fluid. *Baskaran et al*.[39] investigated the effect of zirconium oxide nanoparticles on the performance of a domestic refrigeration system designed for R134a. The performance qualities of the refrigerator were assessed using nanorefrigerant (ZrO_2-R134a) consisting of 0.2 g l^{-1} of nanoparticles as a drop-in alternative for the regular refrigerant. The findings revealed that using nanorefrigerant improved the system's performance. Compared to the performance of the standard refrigerant, the COP of the nanorefrigeration system increased, while its compressor exit temperature and power use decreased by 6.50 and 6.25 %, respectively.

To improve the effectiveness of an R134a refrigeration unit, *Mohamed et al*.[40] developed cerium oxide (CeO_2) and copper oxide (CuO) nanoparticles and mixed them with R134a to generate nanorefrigerants. These nanoparticles of metallic oxide were created using a gas-to-solid method and chemical vapour deposition procedures. Scanning electron microscopy and X-ray diffraction investigations revealed that the nanoparticles were spherical in form. Furthermore, the nanorefrigerants were theoretically evaluated using Ansys-Fluent software. The findings revealed that both cerium and copper oxides increased the cooling capacity and energy efficiency of the refrigeration unit. Operating the refrigerator with CuO/R134a nanorefrigerant resulted in a significant increase, with an average COP of 25 % higher compared to the performance of a conventional R134a refrigerator.

Pipwala et al[41] studied the impact of nanorefrigerants on the operational efficiency of a direct-cooled vapour compression refrigerator initially designed for R600a. The working fluids in the investigation consisted of R600a mixed with nanoparticle concentrations of 0.04 and 0.08 g (CuO). The refrigeration unit was tested using both the initial refrigerant (R600a) and the two nanorefrigerants. The findings demonstrated that the system's performance enhancement could be directly correlated to the quantity of nanoparticles in the refrigerants. Compared to the data obtained with the pure refrigerant, the average energy consumption decreased by 8.2 and 12.89 % for the 0.04 and 0.08 g concentrations, respectively.

4.3 Challenges in the application of nanolubricants and nanorefrigerants

The application of nanolubricants and nanorefrigerants in refrigeration systems presents several challenges. These include the difficulty of preparing homogeneous and stable blends, as well as the potential for decomposition and aggregation, which can cause blockages or fouling within the system. Additionally, the cost of preparation and the need for specialised equipment to process nanofluids are significant barriers. There are also concerns regarding the environmental impact and toxicity of nanoparticles. It is also vital to ensure that the system's lifespan and overall functionality are not compromised in any way.

5 Modifications to the refrigeration cycle

Modifying the refrigeration cycle can play a critical role in reducing the power consumption, increasing cooling capacity, and improving the system's COP. Several adjustments to refrigeration cycles have recently been developed to enhance the performance of cooling systems, and examples of these modifications include the use of cascades, the addition of internal heat exchangers, and the incorporation of ejectors.

5.1 Cascade cooling systems

A cascade cycle is basically a series of single-stage vapour compression cycles in which the condenser of the lower-temperature cycle transfers heat to the evaporator of the upper-temperature cycle. Cascade cooling systems employ at least two vapour-compression cycles with different cooling agents. The lower-temperature system uses an evaporator to remove heat from the cooling chamber. This heat is then transferred to a heat exchange device (condenser) that is cooled by the evaporator of the upper-temperature system's refrigerant.[42] Fig. 7 presents a schematic of a two-stage cascade refrigeration cycle. This system utilises two distinct vapour compression cooling cycles, each with its own refrigerant, and a heat exchange device to transfer heat from one cycle to the other. The condenser in the low-temperature stage serves as the evaporator for the high-temperature stage, enabling exceptionally low temperatures. One cycle cools the other, resulting in a considerably lower temperature. One of the main advantages of cascade systems is their ability to achieve lower temperatures than single-stage systems. This is because cascade systems use multiple refrigerants with different boiling points, allowing for greater temperature differentials between stages. In some laboratory and industrial applications that involve a low cooling temperature, cascade refrigeration systems are a viable option. Compared to single-stage compressors of the same capacity, they use less energy and produce lower compressor discharge temperatures.

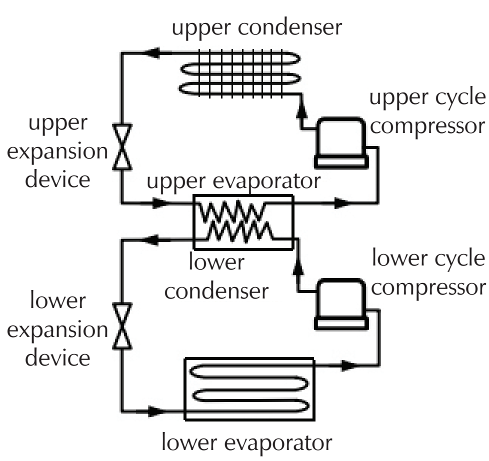

Fig. 7 – Schematic of a two-stage cascade cooling cycle

Udroiu et al.[42] analysed the energy and operational efficiency of a two-stage ultra-low-temperature cascade system across six different cycles. The study applied R170 and R290 as refrigerants for the low- and high-temperature cycles, respectively, to optimise the middle cascade temperature and enhance the COP of the system. The findings revealed that the ideal intermediate cascade temperature varied significantly between −37 and 2 °C. This greatly enhanced the system's energy efficiency, with a 40% increase in COP compared to the conventional setup.

To enhance the performance of a three-stage cascade freezing system used in industrial refrigeration, *Li et al.*[43] incorporated vapour injection into the refrigeration cycle for ultra-low-temperature freezing applications, utilising R600a/R1150, R600/R1150, and R290/R1150 refrigerant pairings. Using the particle swarm optimisation technique, the performance of the redesigned cycle under various operating conditions was examined and compared with that of a traditional cascade cooling cycle. The theoretical analysis found that the R600/R1150 refrigerant pair was the most effective among the three combinations. This pairing improved the volumetric cooling capacity and COP by 58.2 and 53.8 %, respectively.

Tan et al.[44] investigated the performance of a component-based two-stage cascade cooling system using a combination of R600a and R170 refrigerants. The study substituted a compressor with two suction ports for a conventional compressor. A mathematical framework was developed to compare the system's performance characteristics with a single-stage compression cooling system. The results revealed that the two-stage cascade cooling system outperformed the conventional single-stage compression process. The cascade system's evaporator achieved a very low temperature of −60 °C. Compared to single-stage compression, the cascade system exhibited a higher COP of 0.42 and reduced power consumption by 47.03 %.

Llopis et al.[45] designed, constructed, and tested the energy efficiency of a cold room equipped with an auto-cascade cycle to achieve an ultra-low temperature of −80 °C. The study employed three different R600a/R1150 blends as working fluids with mass percentages of 75/25, 70/30, and 65/35 %, respectively. The experimental results revealed that the refrigerant mixture with a 30/70 % mass composition performed better across various operating conditions. The auto-cascade cycle exhibited higher efficiency compared to the non-cascade cycle using the same R600a/R1150 mixture (30/70 % by mass). The cooling capacity increased from 87 to 139 kW.

5.1.1 Shortcomings and economic viability of cascade refrigeration systems

Cascade cooling systems have certain limitations. These include the potential for reduced efficiency if not optimised properly, higher acquisition costs due to the systems' numerous components, and increased complexity. Furthermore, careful selection of working fluids (refrigerants) is essential to balance performance and environmental impact. The intricate nature of cascade systems often requires specialised design and maintenance, especially for applications targeting ultra-low temperatures. Despite these challenges, cascade refrigeration systems are generally considered economically feasible, especially for operations requiring ultra-low temperatures. Their higher COP results in lower operating costs compared to single-stage systems, making them a cost-effective option for industries such as food processing, scientific research, and medical storage. They are commonly used for storing heat-sensitive products such as blood and vaccines. However, the economic feasibility of these systems is heavily influenced by factors such as refrigerant combination, system design, and operating conditions.[46]

Conventional single-stage compression refrigeration struggles to achieve ultra-low temperatures while maintaining efficiency, as it is only suitable for moderate cooling. Because of the high pressure lift ratio necessary for the compression process, ultra-low temperature cooling requires more than one stage of cascade compression. Compared to a single-stage system, the cascade design provides for more efficient heat transfer between compression stages, resulting in a significantly higher COP, reduced energy consumption, and lower operating costs.[44] By selecting appropriate refrigerant pairings for each compression stage, cascade systems can efficiently deliver ultra-low temperatures while also supporting moderate cooling applications. While initial installation costs for cascade systems may be high due to their complexity, the long-term energy savings offset these expenses in scenarios requiring low-temperature cooling.[47]

5.2 Application of internal heat exchanger

An internal heat exchanger (IHX), also known as a liquid-line-suction heat exchanger, facilitates heat exchange between the refrigerant at the condenser and evaporator outlets. This heat exchange ensures sufficient sub-cooling at the condenser outlet, reduces the vapour content of the refrigerant at the evaporator inlet, and increases the latent heat component. Consequently, the cooling capacity of the evaporator is enhanced due to the increase in enthalpy during the evaporation process. In the same way, the process increases the temperature of the refrigerant, causing superheating at the compressor inlet.[48] Fig. 8 presents a schematic of a vapour compression refrigeration cycle with an IHX. It is a system that incorporates a specialised heat exchanger into the cycle to transfer heat between the liquid refrigerant exiting the condenser and the vapour refrigerant leaving the evaporator. This maximises latent heat transfer in the evaporator while reducing the risk of liquid clogging in the compressor. This technique efficiently superheats the vapour refrigerant and sub-cools the liquid, thereby improving the overall efficiency of the cooling system. The effects of an internal heat exchanger in a vapour compression air conditioning system using R22 and R32 as working fluids were investigated theoretically by *Sihombing et al*.[49] The theoretical analysis was conducted using ASPEN PLUS software in an evaporating temperature range of −5 to 5 °C. The results showed that R32 exhibited better performance in the system with an internal heat exchanger (IHX) than R22. Specifically, the IHX increased the COP of the system by 37.04 and 24.14 % when using R32 and R22 refrigerants, respectively.

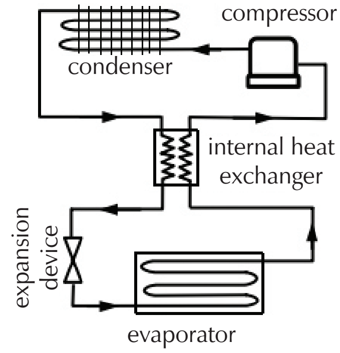

Fig. 8 – Schematic of a refrigeration cycle with IHX

Al-Obaidi et al.[50] explored an effective approach to enhancing the performance of a vapour compression cooling system by incorporating a liquid-line-suction heat exchanger. The test results revealed that the optimised system performed better, achieving a 10 % increase in volumetric cooling capacity. *Oton-Martinez et al*.[51] investigated a water-to-water heat pump system whose cycle had been modified by the installation of an internal heat exchanger. The enhanced system was conceptually and experimentally analysed to evaluate the effect of the internal heat exchanger on the performance coefficient and power consumption. The findings revealed that the modified system's COP and power consumption increased by 7.55 and 4.08 %, respectively. Furthermore, the simulations demonstrated that enlarging the heat exchange area improved both the effectiveness of the internal heat exchanger and the overall system performance.

Jasim et al.[52] conducted a theoretical analysis to evaluate the benefits of incorporating internal heat exchangers in refrigeration systems. The work specifically examined the effects of integrating liquid-suction heat exchangers within a vapour compression cooling system. The primary goal was to ensure that the refrigerant entering the expansion device was in liquid form. Utilising computational fluid dynamics software, the study examined the influence of temperature on the heat exchange mechanism. The results indicated that the length of the heat exchanger determined the system's functionality improvement. A significant increase in COP was observed when the heat exchanger length exceeded 300 mm. The COP of the refrigeration cycle increased due to the sub-cooling of the refrigerant liquid by the heat exchanger.

Oshodin et al.[14] studied the efficiency of an internal heat exchanger (IHX) in a refrigeration unit that combined liquefied petroleum gas and carbon dioxide as the working fluid. Comparative experiments were conducted on systems with and without an IHX to establish their efficiency. The thermophysical characteristics of the refrigerant mixture were determined using the REFPROP software. The findings revealed that the system with an IHX achieved a higher COP of 1.398 compared to the system without an IHX. Statistical analysis of the experimental data revealed significant differences between the two systems (p-value < 0.033 for the paired samples t-test). The analysis also confirmed with a 95 % confidence level that the COP of the system with IHX was statistically superior to that of the system without IHX.

5.2.1 Shortcomings of internal heat exchangers

The use of IHXs in refrigeration systems is associated with several limitations. These include the potential for liquid slugging, reduced effectiveness due to fouling, and increased complexity in design and maintenance. IHXs may also have limited heat transfer capability when compared with auxiliary heat exchangers. If not properly managed, these factors can adversely affect the overall efficiency of the system.

5.3 Application of ejectors in refrigeration systems

The integration of ejectors represents another adaptation to traditional vapour compression cycles, as well as a recent advancement in refrigeration systems. An ejector is a static device, without moving parts, that uses a high-velocity, high-pressure fluid to transport a low-pressure fluid to a higher-pressure fluid at the diffuser discharge. Ejectors can function either as an expansion device or as a compressor. Fig. 9 illustrates the geometrical configuration of an ejector.

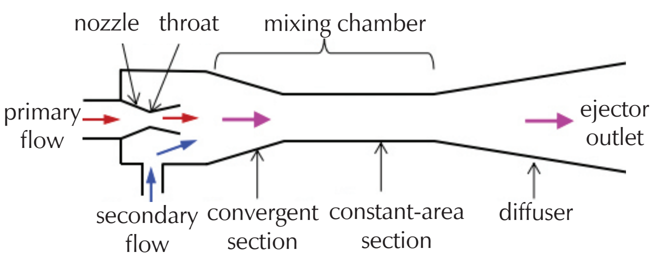

Fig. 9 – Geometrical configuration of an ejector

An ejector operates on the principle of high-pressure fluid jets to generate a pressure difference. It comprises a nozzle that speeds up the high-pressure working fluid, a compartment for mixing to absorb the refrigerant vapour, and a diffuser that restores pressure before transferring the refrigerant to the condenser. The ejector effectively absorbs and compresses low-pressure refrigerant vapour from the evaporator. It functions as a compressor with no movable components, enabling a refrigeration cycle powered by heat energy rather than electricity. The technology is gaining popularity due to its cost-effectiveness, absence of moving parts, ability to handle dual-phase fluids, and most importantly, its potential to enhance refrigeration system performance by reducing throttling and compression inefficiencies.[32]

Fig. 10 illustrates a vapour ejector refrigeration system, which replaces the traditional compressor with an ejector for compressing the vapour refrigerant. The system allows the high-pressure primary refrigerant vapour to accelerate through a nozzle, creating a low-pressure zone that draws in the low-pressure secondary refrigerant from the evaporator. It blends the two refrigerants and compresses the mixture before discharging it into the condenser. The system employs the energy of a high-pressure fluid to draw in and compress a low-pressure fluid, resulting in cooling without the need for a conventional compressor.

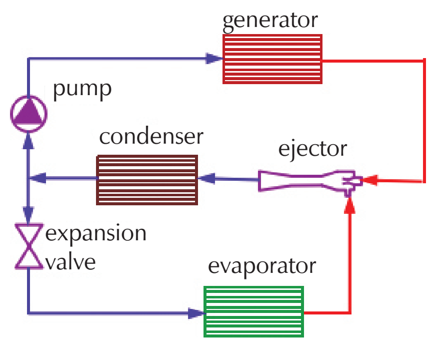

Fig. 10 – Vapour ejector refrigeration cycle

Chen et al.[33] conducted a theoretical evaluation of a vapour ejector refrigeration system designed for air conditioning application, operating under sub-critical and critical modes. R134a and R290 were used as working fluids, and the system's performance was analysed across various operating conditions. The theoretical findings revealed that the COP of the vapour ejector cycle decreased at high-condensing and low-evaporating temperatures for R290 and R134a, respectively, under critical modes of operation. Conversely, during the same mode of operation, the COP for R290 and R134a increased significantly at low-condensing and high-evaporating temperatures, respectively.

Fig. 11 shows an ejector refrigeration cycle with a booster. In this configuration, a mechanical compressor, referred to as a booster, is employed to pre-compress the refrigerant vapour exiting the evaporator before it enters the ejector. The booster enhances the cooling capacity and overall efficiency of the refrigeration cycle. By significantly increasing the pressure, the booster enables the ejector to effectively elevate the pressure to the condenser level. *Takleh* and *Zare*[34] conducted a comprehensive thermodynamic analysis of an optimised ejector-expansion refrigeration cycle. The study simulated six different refrigerants and three systems: an ejector optimised with a booster, a standard ejector, and a conventional vapour compression system, all under constant-pressure mixing mode. The systems were evaluated for exergy efficiency at constant condensing and evaporating temperatures of 40 and 5 °C, respectively. The analysis demonstrated that the optimised system outperformed the other two systems. In addition, among the six refrigerants, R1234ze exhibited the highest exergy efficiency, achieving values that were 15.5 and 5.7 % higher than those reported for the conventional vapour compression and standard ejector refrigeration systems, respectively.

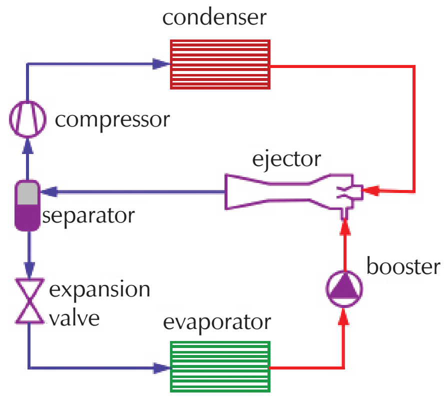

Fig. 11 – Ejector refrigeration cycle with booster

Fig. 12 illustrates a refrigeration system equipped with a dual-phase ejector. This system incorporates a specialised ejector designed to operate with a dual-phase refrigerant blend containing both vapour and liquid phases during the expansion cycle. This enables more efficient energy utilisation compared to a conventional expansion valve, thereby enhancing the system's cooling capacity and overall efficiency. *Sutthivirode* and *Thongtip*[35] investigated the performance improvement of a dual-phase ejector integrated into a refrigeration system and compared it with the performance of a standard vapour-compression refrigeration system. The study developed an experimental test rig capable of producing chilled water under various cooling demands. The results revealed that the dual-phase ejector system achieved chilled water temperatures of 2 °C, compared to 12 °C in the conventional refrigeration system under identical operating conditions. In addition, the dual-phase ejector system's COP was 12.7 % higher.

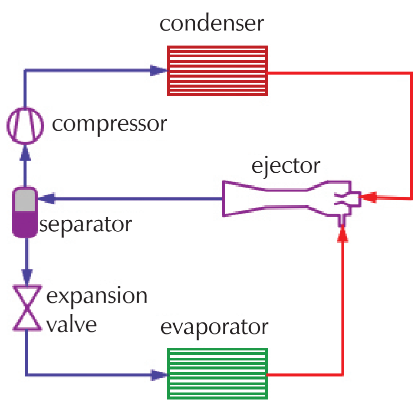

Fig. 12 – Refrigeration system with dual-phase ejector

5.3.1 Shortcomings of vapour ejectors

Vapour ejectors may potentially pose problems if not properly optimised. Their performance depends on specific configuration settings, such as mixing chamber size and nozzle design, which must be tailored to the fluid characteristics, pressure levels, and flow rates, all of which can lead to operational unreliability. Ensuring steady functioning of an ejector can also prove challenging. They are often physically larger than traditional compressor designs due to the more complex components required to achieve the desired pressure difference. They might additionally require higher energy input to deliver an equivalent cooling output as a conventional compressor, resulting in a lower COP.

6 Reducing heat load to improve efficiency

Reducing the heat load is another cost-effective method for improving efficiency of refrigeration systems and lowering energy consumption. The cooling requirement decreases with heat load reduction with respect to time of usage as well as power consumption rating. Two advantages arise from reducing the electrical load of fixtures like fans and lights in temperature-controlled spaces. Lighting, which is a constant load in air-conditioned or refrigerated spaces, generates heat that can only be removed by the cooling equipment. This creates a double burden: in addition to the electricity cost for lighting, there is an additional cost for the energy required by the air conditioning and refrigeration units to remove the heat emitted by the lights.[36]

Effective door management can help reduce the heat load by preventing air from higher-temperature surroundings or the ambient environment from entering the refrigerated or temperature-controlled area. The infiltration of warm air into chilled and cold chambers increases the heat load and moisture content. Consequently, the refrigeration equipment is forced to consume more energy to maintain the chambers at the desired temperature.[37] *Brown et al.*[37] introduced a transparent door to reduce heat penetration in an open-faced chilled food display cabinet. Their study found that adding a door reduced the cabinet's maximum temperature from 7.4 to 3.6 °C, resulting in a 51.5 % reduction in electricity consumption.

The compressor, responsible for increasing the pressure of the refrigerant before sending it to the condenser, is the most energy-intensive moving component in a refrigeration system. In order to extract heat from the refrigerated area, the refrigerant must condense and change into a cold liquid, which cannot happen without the compressor. Compressors consume 80 to 90 % of the total energy consumption of a standard refrigeration system.[38] The cooling capacity and performance of a refrigeration system are directly influenced by the speed of the compressor. Higher speeds allow the compressor to process more refrigerant gas, enhancing the heat transfer rates and overall cooling capacity. However, the compressor in a typical refrigeration system operates at a constant speed to deliver the optimum cooling capacity at maximum heat load.[38] This results in unnecessary energy consumption during periods of lower heat load. Variable-speed compressors, on the other hand, can adjust their speed based on the heat load at any given time, resulting in reduced power consumption.

7 Conclusion

Population growth, industrialisation, and technological innovations have contributed to an increased reliance on air conditioning and refrigeration systems, resulting in higher energy consumption. To curb this rising demand, improving the efficiency of refrigeration systems is vital. High-performance refrigeration systems not only reduce energy consumption but also play a vital role in mitigating climate change through increased energy efficiency. Technological innovation has been a key driving force behind performance improvement of refrigeration systems. This review explores various strategies for enhancing the performance of air conditioning and refrigeration systems, which are now among the largest energy consumers in both residential and non-residential buildings. Several approaches to replacing environmentally harmful refrigerants are also discussed. Alternative refrigerants must combine energy-efficiency, a high COP, and substantial cooling capacity while maintaining low environmental impact. Although installing new systems to meet environmental standards and improve energy performance may entail significant upfront costs, these investments may ultimately prove to be the most cost-effective over the lifespan of the appliance.

Nanolubricants and nanorefrigerants are two popular applications of nanotechnology in refrigeration systems that are elaborately discussed. They improve heat transfer in the system. Nanolubricants increase the system performance by boosting the tribological qualities of the compressor oil, thanks to their superior thermal conductivity compared to base oils. Nanorefrigerants are base refrigerants enriched with nanoparticles. The addition of nanoparticles to conventional refrigerants increases heat transfer and the thermophysical properties of nanorefrigerants. This article discusses various methods for improving the performance of air conditioning and refrigeration systems. These include replacing traditional refrigerants with new ones through drop-in and retrofitting replacement, reducing heat loads, and incorporating other cutting-edge technologies such as ejectors, internal heat exchangers, and cascade systems, which can significantly improve refrigeration system performance.

The presented alternative refrigeration systems not only reduce the carbon footprint by using working fluids with a significantly lower global warming potential, but also conserve energy during cooling operations. Furthermore, advanced refrigeration technologies dramatically minimise the carbon footprint by reacting to evolving circumstances, permitting continuous control, and optimising system functionality, leading to substantially reduced energy consumption and greenhouse gas emissions. In general, this article identifies effective strategies for enhancing refrigeration system performance to improve energy efficiency, reduce energy consumption, and minimise operating costs. These energy-saving solutions will also benefit the environment by reducing the carbon footprint and greenhouse gas emissions associated with refrigeration and air conditioning systems.

List of abbreviations

CFC	– chlorofluorocarbon
COP	– coefficient of performance
GWP	– global warming potential
HCFC	– hydrochlorofluorocarbon
HFC	– hydrofluorocarbon
HFO	– hydrofluoroolefin
HVAC	– heating, ventilation, and air conditioning
IHX	– internal heat exchanger
ODP	– ozone depletion potential
POE	– polyolester

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SAŽETAK

Pregled tehnika za poboljšanje učinkovitosti rashladnih sustava

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Poboljšanje učinkovitosti rashladnih i klimatizacijskih sustava doprinosi energetski učinkovitijim zgradama te donosi značajne koristi za okoliš. Tehnološke inovacije ključni su pokretač u unaprjeđenju rada rashladnih sustava. Ovaj članak donosi pregled provjerenih strategija za optimizaciju performansi klimatizacijskih i rashladnih sustava, koji i dalje spadaju među energetski najzahtjevnije potrošače energije u zgradama. U radu se naglašava da potraga za alternativama rashladnim sredstvima koja oštećuju ozonski sloj i imaju visok potencijal globalnog zagrijavanja ne bi trebala biti usmjerena samo na ekološki prihvatljiva sredstva, već i na ona koja su energetski učinkovitija i imaju viši koeficijent učinka u odnosu na sredstva koja zamjenjuju. Također se ističe važnost razmatranja potencijala modernizacije postojećih sustava kao načina poboljšanja njihove učinkovitosti. Iako ugradnja potpuno novih sustava može biti potrebna za postizanje vrhunske kontrole okolišnih uvjeta i energetske učinkovitosti, takav pristup često zahtijeva visoka početna ulaganja. Unatoč tome, dugoročno se može pokazati kao najisplativije rješenje.
U članku se također istražuju dvije primjene nanotehnologije koje mogu poboljšati prijenos topline u rashladnim sustavima. Ostale suvremene tehnologije, analizirane su s obzirom na njihov potencijal da znatno unaprijede izvedbene značajke sustava. Ukupno gledano, ovaj rad nudi sveobuhvatnu procjenu dostupnih metoda za unaprjeđenje izvedbenih značajki klimatizacijske i rashladne opreme te pruža vrijedne uvide za istraživače u tom području.

Ključne riječi
Potrošnja energije, energetska učinkovitost, nanorashladno sredstvo, poboljšanje izvedbenih značajki, rashladni sustav

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