

Review of Utilization of Alternative Energy for Refrigeration

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Abstract

Refrigeration plays a vital role in modern life, with approximately 4.5 million refrigerators used worldwide each year. Most of these systems rely on conventional refrigerants such as R-12 and R-22. These chemicals create serious environmental effects such as they deplete the ozone layer and fuel climate change, largely because of their extremely high ozone depletion potential (ODP) and global warming potential (GWP). Growing environmental concerns and strict international regulations have made it essential to explore alternative refrigerants and sustainable refrigeration technologies. To address these issues, researchers are focusing on eco-friendly refrigerants that provide effective cooling performance while minimizing environmental impact. In addition to refrigerant substitution, the use of alternative energy sources and innovative refrigeration techniques has gained considerable attention. Technologies such as thermoelectric refrigeration, magnetic refrigeration, solar absorption systems, vortex tube refrigeration, and pulse tube refrigeration offer promising solutions. These systems operate without harmful refrigerants or significantly reduce their usage, making them environmentally sustainable, to avoid such problem it is necessary to use some alternative refrigerant which is eco friendly and which gives performance for refrigeration process with least effective cost. It also found that there are alternative source of energy which will use for refrigeration process, By using alternative source like thermoelectric, magnetic, solar absorption, vortex tube, pulse tube, refrigeration process can be done with effective performance and avoid the above said problem. This paper aims to focus on a thorough look at refrigeration's history, spotlighting how it has evolved from conventional systems to cutting-edge, sustainable technologies It also examines various alternative energy-based refrigeration methods, their working principles, advantages, limitations, and potential applications. The study emphasizes the importance of adopting eco-friendly refrigeration technologies to achieve energy efficiency, environmental protection, and cost-effectiveness. Such advancements are crucial for developing sustainable cooling solutions to meet future global demands.

Keyword: Conventional refrigerant, eco-friendly, alternative refrigerant, global warming, environmental, sustainable

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INTRODUCTION

History of Refrigeration

Refrigeration, in its modern form, began to take shape during the mid-19th century, alongside the Industrial Revolution. This period saw major progress in thermodynamics, which helped scientists and engineers understand the behavior of heat and energy. These discoveries have played an important role in the development of refrigeration systems. However, the idea of preserving food using cold temperatures is much older and dates back to ancient times. It is believed that early humans used natural cold environments for preservation. For

example, Paleolithic communities' likely stored meat in pits dug into the frozen ground (permafrost), a method that has continued in some Arctic cultures for centuries. Subsequently, the use of ice became more organized. Historical records show that the Chinese used ice houses as early as 1000 BC. Similarly, the Romans and Persians collected and stored ice and snow to cool their beverages during hot seasons [1–11].

Between the 17th and 19th centuries, the use of natural ice became widespread, particularly in Europe and America. A major breakthrough occurred in 1755 when Professor William Cullen demonstrated artificial refrigeration by producing ice through the evaporation of water under reduced pressure. He also experimented with ethyl ether and observed that its evaporation caused cooling.

In 1834, Jacob Perkins developed and patented the first practical vapor-compression refrigeration system using ethyl ether in a closed-loop system. Although effective, ethyl ether is highly flammable and poses safety risks. To address this, Charles Tellier introduced methyl ether in 1863, which operated at higher pressure and reduced the chances of air entering the system and causing an explosion. Further improvements were made by James Harrison in Australia, who used methyl ether. Around the same time, Carl von Linde made significant contributions to refrigeration technology and was often credited with advancing the use of ammonia as a refrigerant. However, the first ammonia compressor was built earlier in 1872 by David Boyle, who produced many such systems for preserving and transporting meat. Ammonia is an efficient refrigerant owing to its excellent thermodynamic properties; however, its toxicity remains a concern. Therefore, alternative refrigerants were explored. In 1862, Lowe developed a refrigeration system using carbon dioxide. Although CO₂ is less toxic, it requires high operating pressures and has limitations owing to its low critical temperature (Table 1).

By the late 19th century, another refrigerant, methyl chloride, was introduced in France. This later became the basis for the development of halocarbon refrigerants. However, methyl chloride is toxic and flammable, leading to several accidents. Compared to this, substances such as sulfur dioxide and ammonia, although toxic, have strong odors that make leaks easier to detect and thus somewhat safer in practice.

Need for Alternative Refrigerant and Alternative Energy

To comply with the Montreal Protocol, it is essential to gradually eliminate traditional refrigerants and replace them with environmentally safer alternatives. This global agreement aimed to reduce the substances responsible for ozone layer depletion and promote sustainable refrigeration practices. One of the earlier widely used refrigerants, R-12, has certain limitations. Although it is safe, stable, non-flammable, and relatively inexpensive, it requires a larger compressor to achieve the same cooling effect as ammonia-based systems, which are more efficient but highly toxic.

Table 1. Shows the list of phased out refrigerant given by Montreal Protocol [5].

Ozone depleting substance	Developed countries (current status)	Developing countries (current status)
Chlorofluorocarbons (CFCs)	Completely phased out since 1996	Completely phased out since 2010
Halons	Phased out by 1994 (only essential uses allowed)	Phased out by 2010
Carbon tetrachloride (CTC)	Eliminated by 1996	Fully phased out by 2010
Hydrochlorofluorocarbons (HCFCs)	Fully phased out by 2020 (with minor servicing exemptions up to 2030)	Gradual phase-out ongoing: 67.5% reduction by 2025, complete phase-out by 2040
Hydrobromofluorocarbons (HBFCs)	Completely phased out by 1996	Completely phased out by 1996
Methyl chloroform	Phased out by 1996	Fully phased out by 2015
Methyl bromide	Phased out by 2005 (except critical uses)	Phased out by 2015 (with limited exemptions)

This drawback initially limited its performance, despite its safety advantages. The introduction of R-22 (CHClF₂) addressed some of these issues. It offers better efficiency and requires compressor sizes comparable to those of ammonia systems, making it a practical alternative. Over time, R-22 has replaced R-12 in many applications, such as marine refrigeration, and has even substituted ammonia in some industrial uses. However, R-22 was not perfect—it was less chemically stable, produced higher discharge temperatures in compressors, and provided less effective motor cooling in sealed units [1].

To overcome these challenges, a new refrigerant blend, R-502, was developed. It is an azeotropic mixture of R-22 and R-115. This combination allows refrigeration systems to operate efficiently even under extreme conditions, such as high condensing pressures and very low evaporating temperatures, particularly in single-stage systems. Since the 1930s, chlorofluorocarbons (CFCs), such as R-12, have been widely used because of their excellent properties, particularly in domestic refrigeration and small cooling systems. However, scientific research later revealed that CFCs significantly contribute to ozone layer depletion and enhance global warming. Consequently, alternative refrigerants have been developed. One of the most successful replacements is R-134a (CH₂F–CHF₃). Its thermodynamic properties are similar to those of R-12, making it a suitable substitute. Importantly, R-134a does not contain chlorine, which means that it has a nearly zero ozone depletion potential. It is also nontoxic and nonflammable, with operating pressures similar to those of R-12 [6, 7].

Despite these advantages, R-134a has some limitations. It is generally more expensive, slightly less energy-efficient, and incompatible with traditional lubricants used in older systems. Although it is safer for the ozone layer, it still contributes to global warming owing to its global warming potential (GWP), although to a lesser extent than earlier refrigerants [7–9].

Alternative Energy for Refrigeration

Most conventional refrigeration systems operate using a reversed Rankine cycle (vapor compression system). However, owing to environmental concerns and the need for sustainable solutions, several alternative refrigeration methods have been explored. These systems either modify the traditional cycle or use entirely different working principles [10]. Some important alternative refrigeration technologies are explained below.

Thermo-Electric Refrigeration

Thermoelectric refrigeration operates based on the Peltier Effect. When an electric current passes through a circuit made of two different materials, heat is absorbed at one junction and released at the other junction. In metallic materials, this effect is negligible owing to their high thermal conductivity. However, when semiconductor materials are used, the cooling and heating effects become significant and useful for energy harvesting.

- *Advantages:* No moving parts, silent operation, compact and reliable, can operate using solar energy (no need for continuous electricity supply)
- *Disadvantages:* Much lower efficiency compared to vapor-compression systems, and not suitable for large-scale applications such as buildings
- *Applications:* Cooling of small electronic components, portable refrigeration devices, and space and remote-area cooling systems

Currently, thermoelectric refrigeration is limited to small-scale use; however, improvements in semiconductor materials could expand its applications in the future. The process flow diagram of the thermoelectric refrigeration system is shown in Figure 1.

Air Cycle Refrigeration

Air cycle refrigeration uses air as the working fluid and operates on the Brayton Cycle, which is different from the Rankine cycle used in conventional systems. Although air is freely available and environmentally friendly, the system suffers from low efficiency, making it unsuitable for most commercial applications.

- *Advantages:* Uses air (natural and non-toxic refrigerant), simple system design, and lightweight equipment
- *Disadvantages:* Very low efficiency compared to vapor compression systems, higher energy consumption
- *Applications:* Aircraft cabin air conditioning (main application), experimental use in railways, and large-scale freezing systems

Owing to its inefficiency, air-cycle refrigeration is not widely used in buildings despite its simplicity. The process flow diagram of the air refrigeration system is shown in Figure 2.

Water Vapor Compression

Water can also be used as a refrigerant in a modified vapor-compression system based on the Rankine cycle. It has excellent thermodynamic properties, such as a very high latent heat of evaporation and a high critical temperature, which make water a potentially efficient refrigerant.

- *Advantages:* Environmentally friendly (natural refrigerant), high cooling potential
- *Disadvantages:* Extremely high specific volume (requires very large compressors) and complex and costly system design

To address this issue, engineers have developed high-speed, multistage axial compressors; however, this technology is still under development and has not yet been widely successful.

The process flow diagram of the water vapor compression refrigeration system is shown in Figure 3.

Stirling Cycle Refrigeration

The Stirling cycle engine was invented in 1812 by Robert Stirling to create a safer alternative to early steam engines. At that time, steam engines often operated with low-pressure boilers and crude designs, making them prone to dangerous accidents.

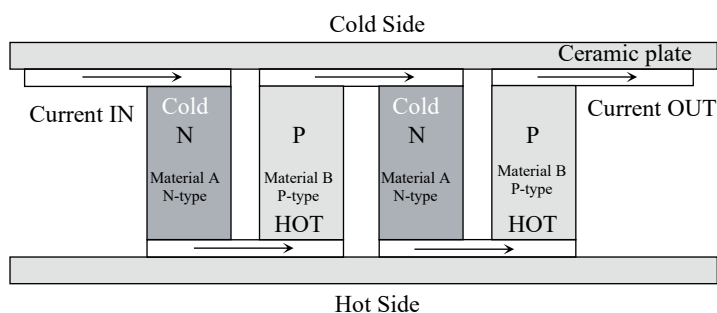


Figure 1. The process flow diagram for thermoelectric refrigeration system.

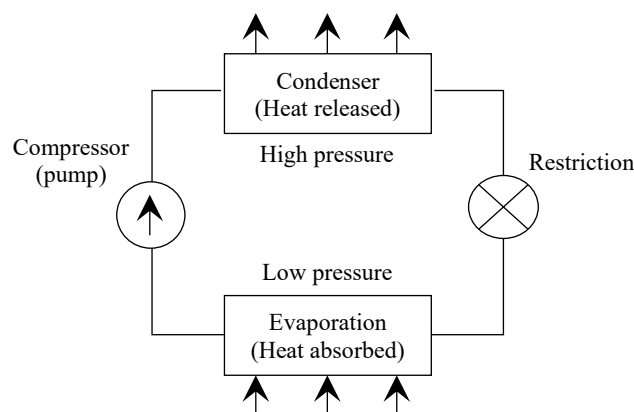


Figure 2. The process flow diagram for the air cycle refrigeration system.

The Stirling engine is an external combustion engine, which means that heat is supplied from an external source rather than being generated inside the engine. In this system, a fixed amount of gas is enclosed in the engine. When heat is applied, the gas expands and pushes the piston, producing mechanical motion through the crankshaft.

- *Advantages:* Safer than steam engines (lower pressure and temperature), environmentally friendly with low emissions, and quiet and smooth operation.
- *Limitations:* Heat transfer is limited because it occurs through the cylinder walls, and the design is complex, involving multiple components such as the power piston, displacer piston, and regenerative heat exchanger, and requires precise synchronization between moving parts

Although Robert Stirling successfully created a safe and reliable engine, its complexity and heat transfer limitations restricted its widespread use [10, 11].

The process flow diagram for the stirling cycler refrigeration system is shown in Figure 4

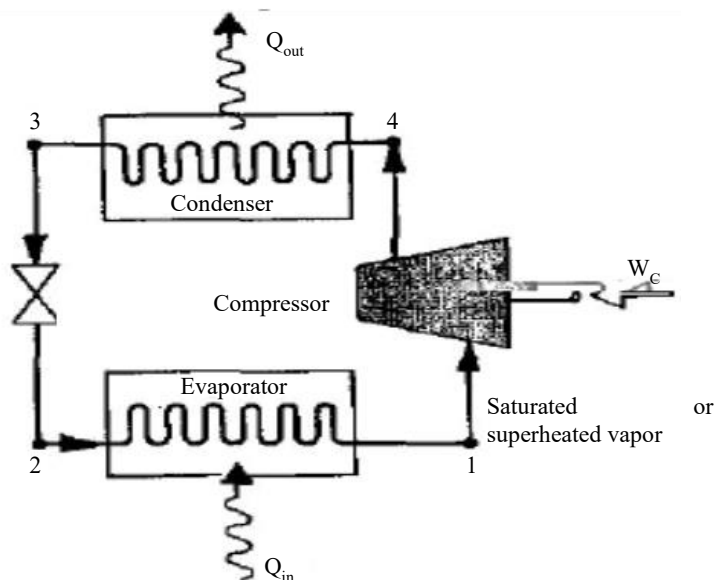


Figure 3. The process flow diagram for the water vapour refrigeration system.

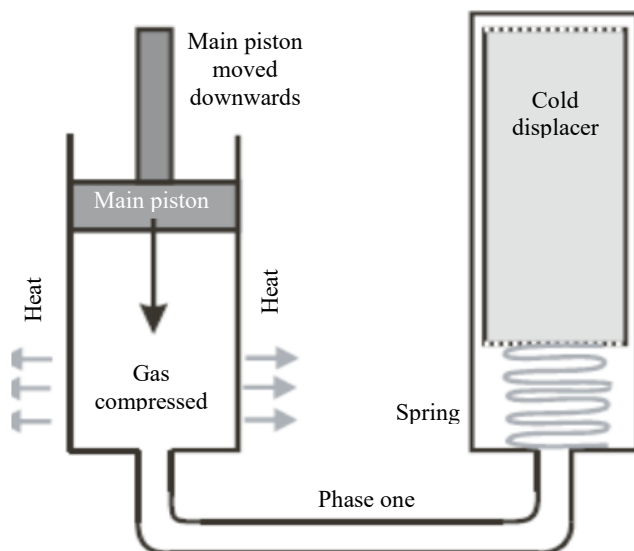


Figure 4. The process flow diagram for stirling cycle refrigeration system.

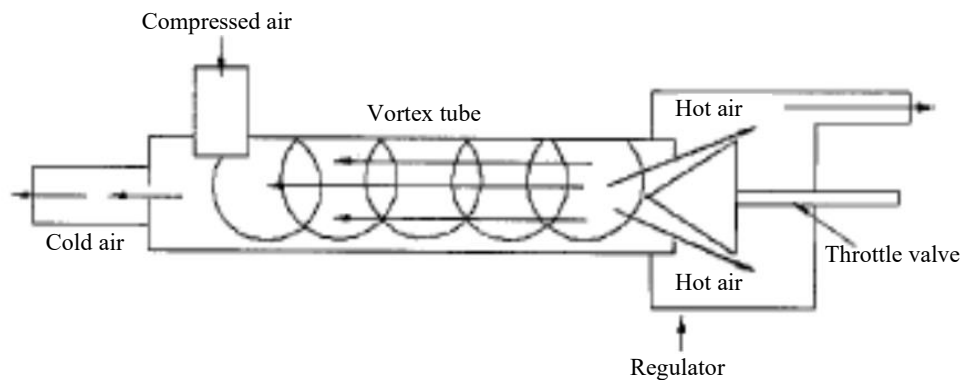


Figure 5. The process flow diagram for vortex tube refrigeration system.

The Vortex Tube Refrigerator

The vortex tube, also known as the Ranque–Hilsch vortex tube, is a unique cooling device that operates without moving parts. It was first developed by Georges J. Ranque in 1931 and later improved by Rudolf Hilsch, which is why it is named after both scientists who developed it. Initially, the working principle of the vortex tube seemed unusual, as it produced hot air at one end and cold air at the other end using only compressed air [12–22].

- *Working principle:* Compressed air enters the tube tangentially, creating a high-speed (vortex) flow inside the tube, and energy separation occurs: high-energy (hot) air moves toward the outer region, and low-energy (cold) air moves toward the inner core [10].
- *Advantages:* Extremely simple construction, no moving parts, low maintenance, high durability, and reliability
- *Disadvantages:* Very low efficiency, not suitable for large-scale refrigeration
- *Applications:* Spot cooling in industrial environments and cooling of tools and equipment under high-temperature conditions [23].

The process flow diagram of the vortex tube refrigeration system is shown in Figure 5.

Pulse-Tube Refrigeration

Pulse-tube refrigeration has emerged as one of the most actively researched areas in cryogenic cooling applications. Its development began with an accidental discovery by William E. Gifford, who observed cooling effects when pressure pulses were applied to one end of a closed tube at low temperatures. Initially, the underlying physics were not fully understood, but later, they were found to be closely related to the earlier work of Thomas J. Hofler. Further advancements were made when Mikulin attempted to improve the heat transfer within the system. Surprisingly, this led to a significant boost in performance [23, 24].

- *Advantages:* No moving parts at the cold end, high reliability, low maintenance, and suitability for cryogenic applications.
- *Applications:* Cooling of infrared sensors in satellites, scientific instruments, and space applications, and precision cooling systems on Earth.

The process flow diagram for the pulse tube refrigeration system is shown in Figure 6

Magnetic Refrigeration

Magnetic refrigeration is based on the Magnetocaloric Effect, which was first discovered in 1881. This effect refers to the change in the temperature of certain materials when exposed to a magnetic field.

Working Principle

When a magnetic field is applied to certain materials (mainly ferromagnetic metals), their magnetic moments align, causing the material to heat up, and when the magnetic field is removed, the material

cools down as the magnetic moments become disordered; this heating and cooling cycle can be used to achieve refrigeration.

One of the most effective materials for this process is gadolinium, which exhibits a strong magnetocaloric effect. However, pure Gd is not very effective at room temperature. To overcome this, modern research has developed improved materials, such as alloys of gadolinium with silicon and germanium, which perform better under normal conditions [25, 26].

- *Advantages:* Environmentally friendly (no harmful refrigerants), higher potential efficiency, and reduced noise and mechanical losses
- *Limitations:* High cost of magnetic materials and technology still under development for large-scale use. The process flow diagram of the magnetic refrigeration system is shown in Figure 7.

Absorption Refrigeration

Absorption refrigeration is a well-established cooling technology, although it currently represents only a small portion of the overall refrigeration and air conditioning market. Unlike conventional systems, they use environmentally friendly refrigerant combinations, such as ammonia–water and water–lithium bromide, which have zero global warming potential (GWP).

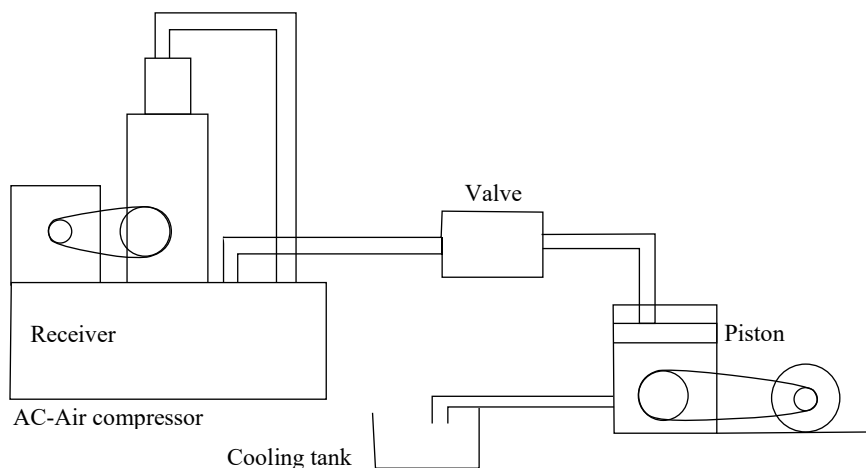


Figure 6. the process flow diagram for the pulse tube refrigeration system.

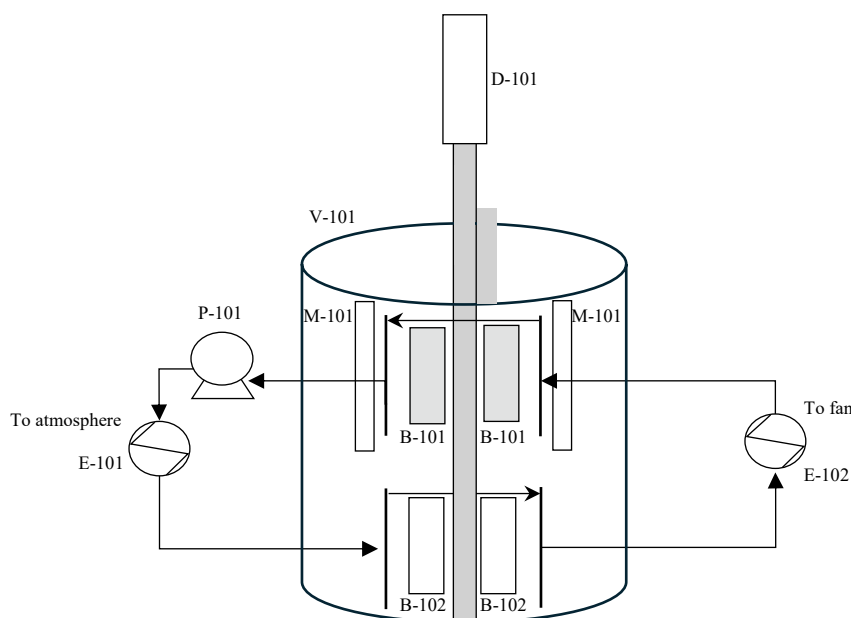


Figure 7. The process flow diagram for the magnetic refrigeration system.

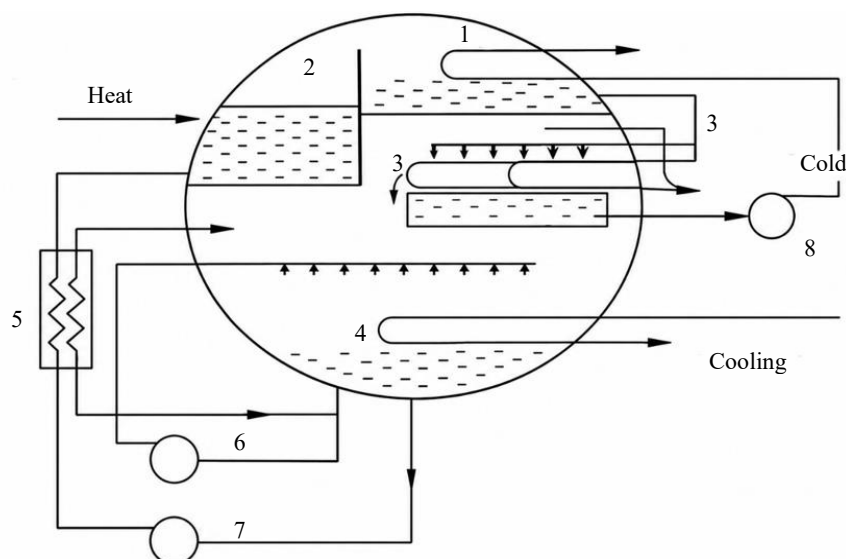


Figure 8. The process flow diagram for the absorption refrigeration system.

The key difference between absorption and conventional systems is their energy sources. Instead of using mechanical work (such as a compressor), absorption systems are driven by heat. This heat can originate from sources such as fuel combustion, solar energy, or industrial waste heat [27, 28].

- *Advantages:* Uses eco-friendly refrigerants (zero GWP), can utilize waste heat or renewable energy sources, low noise, fewer moving parts, and is suitable for locations with limited electricity supply
- *Limitations:* Lower energy efficiency compared to vapor compression systems, higher initial cost and larger system size, and requires continuous heat supply [8, 29–30]

The process flow diagram for the absorption refrigeration system is shown in Figure 8.

Widely Used Refrigerants and Their Characteristics

Air-R729

Air is one of the simplest and most natural refrigerants and is commonly used in gas cycle refrigeration systems, particularly in aircraft cabin cooling. These systems operate on the Brayton cycle. Although air is environmentally safe and readily available, its efficiency is quite low compared to that of conventional vapor compression systems using HCFCs or HFCs. This leads to a higher energy consumption. Recent research by institutions such as the Building Research Establishment and the University of Bristol has explored advanced air-cycle systems capable of providing both heating and cooling in buildings with improved efficiency. However, such systems are not yet widely commercialized because of their high costs and the lack of mass production.

Water-R718

Water is considered an almost ideal refrigerant from both environmental and thermodynamic perspectives, particularly for applications above 0°C. It is safe, non-toxic, and has excellent heat-transfer properties. However, the major limitation of water is its very high specific vapor volume, which is significantly larger than that of common refrigerants. This requires extremely large compressors, which makes the system bulky and expensive. Advanced compressors, such as axial or centrifugal types, can be used; however, they are costly, custom-built, and not readily available. Owing to these limitations, water is currently unsuitable for general air-conditioning applications.

Carbon Dioxide—R744

Carbon dioxide (CO₂) is gaining popularity as a refrigerant because of its excellent environmental properties. They are non-flammable and non-toxic (safe under normal conditions), have zero ozone depletion potential (ODP), and have a very low global warming potential (GWP).

Challenges

Low critical temperature ($\sim 31.3^{\circ}\text{C}$), which reduces efficiency, operates at very high pressures (approximately 100 bar), and requires specially designed equipment. Despite these challenges, CO_2 is increasingly used in automotive air conditioning, supermarket refrigeration systems, and cascade refrigeration systems for low-temperature applications.

Ammonia–R717

Ammonia is one of the oldest and most widely used refrigerants available. It was first synthesized in 1823, and commercial production began in 1913. It has been used for refrigeration since the mid-19th century. Its advantages are excellent thermodynamic properties, high energy efficiency, Zero ODP, and zero GWP.

- *Applications:* Food processing industries, Cold storage facilities and Ice plants
- *Limitations:* Toxic in nature and flammable under certain conditions

However, its strong, pungent odor aids in early leak detection, thereby improving safety during practical use.

Hydrocarbon Refrigerants

Hydrocarbons are highly efficient refrigerants but are flammable, which is their main drawback.

Common hydrocarbon refrigerants include propane (R290), propylene (R1270), butane (R600), and isobutane (R600a).

- *Advantages:* Excellent thermodynamic performance, high energy efficiency, compatibility with mineral oils, and environmental friendliness (low GWP)
- *Limitations:* High flammability $\rightarrow$ requires strict safety measures for safe usage; hydrocarbons are typically used in small sealed systems and applications with low refrigerant charge

CONCLUSION

Refrigeration technology has evolved significantly over time, moving from the use of natural cooling methods, such as ice, to advanced mechanical and alternative refrigeration systems. Initially, refrigerants such as chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) were widely adopted because of their stability, safety, and efficiency. However, their harmful impact on the environment—particularly ozone layer depletion and global warming—has led to global action through agreements such as the Montreal Protocol. Consequently, the focus has shifted toward eco-friendly and sustainable refrigeration technologies. New refrigerants, such as hydrocarbons, ammonia, carbon dioxide, and water, are gaining importance because of their low or zero environmental impact. Simultaneously, alternative refrigeration methods, such as thermoelectric cooling, air cycle refrigeration, absorption systems, pulse-tube refrigeration, magnetic refrigeration, Stirling engines, and vortex tubes, are being explored to reduce dependence on conventional vapor-compression systems.

Each technology offers unique advantages but also has certain limitations. For example, although natural refrigerants are environmentally safe, they may pose challenges related to safety, efficiency, or system design. Similarly, alternative refrigeration systems are promising but often face issues such as low efficiency, high cost, and limited large-scale applicability. A key takeaway is that no single solution fits all the applications. The future of refrigeration lies in selecting the most appropriate technology based on factors such as energy efficiency, environmental impact, cost, and resource availability. Systems that utilize waste heat, renewable energy, or low-emission power sources are particularly promising for sustainable development.

Overall, the refrigeration industry is gradually transitioning toward greener and more energy-efficient solutions. With continued research and technological advancements, these eco-friendly alternatives are expected to play a major role in meeting future cooling demands while minimizing environmental impacts.

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