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* **Corresponding authors**.

rmjoshi.mech@ddu.ac.in

pranavmehta.mech@ddu.ac.in

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A Critical Review of Pulse Tube Cryocooler Technologies and Their Compressor Systems

Rajesh Joshi[1], Pranav Mehta[1]*

1 Department of Mechanical Engineering, Dharmsinh Desai University, Nadiad-387001, Gujarat, India

Abstract

Background/Objectives: Pulse tube cryocoolers (PTCs) are advanced cryogenic refrigeration systems known for high reliability, low vibration, compactness, and absence of moving parts at the cold end. Recent developments in compressor technologies, phase-shift mechanisms, and regenerator optimization have expanded their applications in aerospace, superconducting devices, medical imaging, and quantum technologies. This review critically evaluates recent advancements in pulse tube cryocooler technologies, compressor systems, phase-shift mechanisms, and performance enhancement techniques while identifying research gaps, bottlenecks, and future development opportunities. **Method:** A systematic review was conducted using peer-reviewed studies from Scopus, Web of Science, ScienceDirect, and IEEE Xplore databases covering 2020–2026. Relevant studies were selected based on cryogenic performance, compressor technologies, and experimental or numerical validation. Comparative analyses were performed for pulse tube configurations, phase-shift techniques, compressor systems, regenerator materials, and heat exchanger designs using parameters such as cooling temperature, thermodynamic efficiency, cooling capacity, pressure ratio, and vibration characteristics. The findings were synthesized using comparative tables, performance graphs, and critical analytical discussions. **Findings:** The review revealed that inertance-type and double-inlet pulse tube cryocoolers achieve nearly 15–25% higher thermodynamic efficiency and improved phase synchronization compared with conventional systems. Recent gas-bearing and moving-coil compressors demonstrated approximately 30–40% lower vibration levels and improved operational stability. High-efficiency miniature cryocoolers operating near 150 K achieved cooling capacities above 500 W with reduced acoustic losses. However, thermal leakage, regenerator inefficiency, synchronization instability, and manufacturing complexity remain major bottlenecks. The study further highlights milestone developments and future opportunities involving AI-assisted optimization, advanced regenerator materials, additive manufacturing, and compact low-vibration cryogenic systems. **Significance:** Unlike earlier reviews focused mainly on thermodynamic descriptions, the present study establishes a comparative framework linking pulse tube configurations, compressor technologies, phase-shift mechanisms, and cryogenic performance. The review uniquely integrates technological advancements, bottlenecks, commercialization challenges, and future research directions within a single comprehensive framework.

Keywords: Pulse tube cryocooler; Cryogenic refrigeration; Cam and follower compressor; Phase shift mechanism; Regenerator; Cryocooler performance

1 Introduction

Cryocoolers are compact refrigeration systems designed to achieve cryogenic temperatures, typically ranging from 10 K to 120 K. They are used in cryogenics applications like superconducting magnets, infrared detectors, quantum computers, and space instruments. Cryocoolers made by Gifford-McMahon (GM) were initially created in 1960[1]. Many varieties of cryocoolers, including Stirling, Gifford-McMahon, pulse tube, Joule-Thomson, and Brayton, each own unique benefits and drawbacks concerning chilling capability, effectiveness, dependability, noise level, dimensions, weight, and expense. Cryogenic refrigeration or cryocooling is done with the help of devices which generate such cryogenic temperatures. All of the above-mentioned types of cryocoolers operates mainly with a working cycle. Therefore, the main focus of research and development should be on cryocoolers with the fewest moving parts possible, since they provide several benefits over the displacer and compressor-piston mechanisms now in use. As a result, the last few years have seen a significant expansion of the research and development of pulse tube cryocoolers to showcase astounding advancements and the elimination of moving components from the cryocooler assembly.

2 Review Methodology

This review was conducted using a systematic approach to evaluate recent advancements in pulse tube cryocooler (PTC) technologies and compressor systems. Relevant literature published between 2020 and 2026 was collected from major scientific databases, including Scopus, Web of Science, ScienceDirect, and IEEE Xplore. The search was performed using keywords such as pulse tube cryocooler, pulse tube refrigerator, cryogenic refrigeration, linear compressor, cam and follower compressor, gas-bearing compressor, phase-shift mechanism, inertance tube, regenerator optimization, and low-vibration cryocooler.

The inclusion criteria considered peer-reviewed journal articles, conference papers, and technical studies focusing on pulse tube cryocoolers, compressor technologies, phase-shift mechanisms, and performance enhancement techniques. Studies reporting key performance parameters such as cooling temperature, cooling capacity, thermodynamic efficiency, pressure ratio, and vibration characteristics were prioritized. Non-English publications, duplicate records, unrelated studies, and articles lacking sufficient technical validation were excluded.

The selected literature was analysed using thematic categories including cryocooler configurations, compressor systems, phase-shift mechanisms, regenerator optimization, and emerging applications. Research gaps were identified based on recurring challenges such as thermal leakage, regenerator losses, synchronization instability, vibration issues, and manufacturing complexity. The findings were synthesized through comparative analysis to identify technological trends, bottlenecks, and future research opportunities in advanced pulse tube cryocooler development.

3 Overview

The overview of the review article can be identified from the Table 1. Accordingly, it gives an overall knowledge about type of cryocoolers, key characteristics, limitations and scope for the developments.

3.1 Cryocoolers technology

Cryogenic refrigeration technologies have gained significant attention in recent years owing to their critical applications in superconducting magnets, infrared detectors, aerospace instruments, medical imaging systems, liquefied gas storage, and quantum computing devices[2]. Among the available cryogenic cooling systems, pulse tube cryocoolers (PTCs) have emerged as one of the most promising refrigeration technologies because of their compact design, high operational reliability, reduced vibration, and absence of moving mechanical components at the cold end[3]. Unlike conventional Gifford–McMahon and Stirling cryocoolers, pulse tube cryocoolers eliminate cold-end moving parts, thereby minimizing frictional losses, maintenance requirements, and mechanical wear while improving long-term operational stability[4].

Recent technological advancements between 2020 and 2026 have significantly improved the thermodynamic performance and cooling efficiency of pulse tube cryocoolers through the development of advanced phase-shift mechanisms, optimized regenerator materials, compact compressor systems, and low-vibration cooling architectures[5]. Inertance-type and double-inlet pulse tube cryocoolers have demonstrated superior phase synchronization and enhanced enthalpy flow characteristics, leading to nearly 15–25% improvement in thermodynamic efficiency compared with conventional basic pulse tube systems[6]. Furthermore, recent gas-bearing and moving-coil compressor technologies have reduced vibration levels by approximately 30–40%, thereby improving suitability for aerospace and ultra-sensitive cryogenic applications[7]. High-frequency miniature pulse tube cryocoolers operating near 150 K have also achieved cooling capacities exceeding 500 W while maintaining compact geometry and reduced acoustic losses[8].

Table 1. Related work in the field of pulse-tube cryocooler

Cryocooler Type	Key Characteristics	Advantages	Major Limitations	Recent Developments
Basic PTC	Simplest configuration	Simple construction, low cost	Limited phase control	Improved regenerator materials
Orifice PTC	Uses orifice and reservoir	Better phase shift control	Additional flow losses	Optimized reservoir design
Double-Inlet PTC	Secondary bypass flow	Higher efficiency and reduced regenerator losses	Complex optimization	Active flow control systems
Inertance PTC	Uses inertance tube for phase shift	Superior phase synchronization	Sensitive to geometry	Dual-diameter inertance tubes
Coaxial PTC	Compact concentric structure	Space saving design	Thermal leakage issues	Advanced insulation techniques
Annular PTC	Regenerator located within pulse tube	Compact configuration	Manufacturing complexity	Additive manufacturing approaches
Stirling-Type PTC	High-frequency operation	High efficiency and compactness	Precision manufacturing required	Moving-coil compressor integration
GM-Type PTC	Valve-controlled operation	Reliable low-temperature cooling	Larger size and complexity	Advanced rotary valve systems

Several review studies have previously discussed pulse tube cryocooler thermodynamics, refrigeration cycles, and cooling applications[9],[10]. However, most existing reviews mainly focus on general cryogenic principles and lack comprehensive comparative analyses involving pulse tube geometries, compressor technologies, phase-shift mechanisms, regenerator optimization, and emerging low-vibration systems. In addition, earlier reviews do not sufficiently address recent technological developments such as AI-assisted optimization, additive manufacturing of cryogenic components, gas-bearing compressors, active phase-shift control systems, and compact cryocoolers for quantum technologies and aerospace applications[11]. Furthermore, limited attention has been given to the direct relationship between compressor dynamics, phase synchronization, and overall cryogenic performance.

Therefore, the present review aims to critically evaluate recent advancements in pulse tube cryocooler technologies with special emphasis on compressor systems, phase-shift mechanisms, thermodynamic performance enhancement, and emerging applications. The review systematically compares different pulse tube configurations including basic, orifice, double-inlet, inertance, coaxial, annular, Stirling-type, and Gifford–McMahon-type systems using reported parameters such as cooling capacity, coefficient of performance, pressure ratio, vibration characteristics, and thermal efficiency. The study further identifies major technological bottlenecks including regenerator losses, thermal leakage, synchronization instability, and manufacturing complexity while proposing future research pathways for the development of compact, energy-efficient, and low-vibration cryogenic refrigeration systems.

3.2 Research Contributions

The present review provides a comprehensive and critical assessment of recent advancements in pulse tube cryocooler technologies reported between 2020 and 2026. Unlike earlier review studies that primarily focused on thermodynamic principles or general cryogenic refrigeration systems, this work establishes a direct relationship between pulse tube configurations, compressor technologies, phase-shift mechanisms, and overall cryogenic performance. The review systematically compares different pulse tube cryocooler designs including basic, orifice, double-inlet, inertance, coaxial, annular, Stirling-type, and Gifford–McMahon-type systems using important performance indicators such as cooling capacity, thermodynamic efficiency, pressure ratio, vibration characteristics, and operational stability. In addition, recent developments involving gas-bearing compressors, moving-coil systems, active phase-shift control, and compact low-vibration cryocoolers have been critically evaluated. The study further contributes by identifying major technological bottlenecks, commercialization challenges, and future research opportunities associated with advanced cryogenic refrigeration systems. By integrating comparative analysis, performance trends, and emerging technologies such as AI-assisted optimization and additive manufacturing within a unified framework, the present review provides valuable scientific insights and future guidance for researchers working in the field of pulse tube cryocoolers.

Cryocoolers use a cryogenic fluid like helium, which is cycled through a thermodynamic process using moving parts. The process involves compressing the fluid at room temperature, precooling it in a heat exchanger, and expanding it at low temperature. Next, before entering the compressor intake, the low-pressure fluid precools the high-pressure fluid. Using an evaporator, the cold produced in the expander is transferred from the cold end to the item that needs to be cooled. Cryocoolers come in a variety of forms, and each has unique characteristics. Accordingly, Figure 1 gives the overall categories of the different cryocoolers.

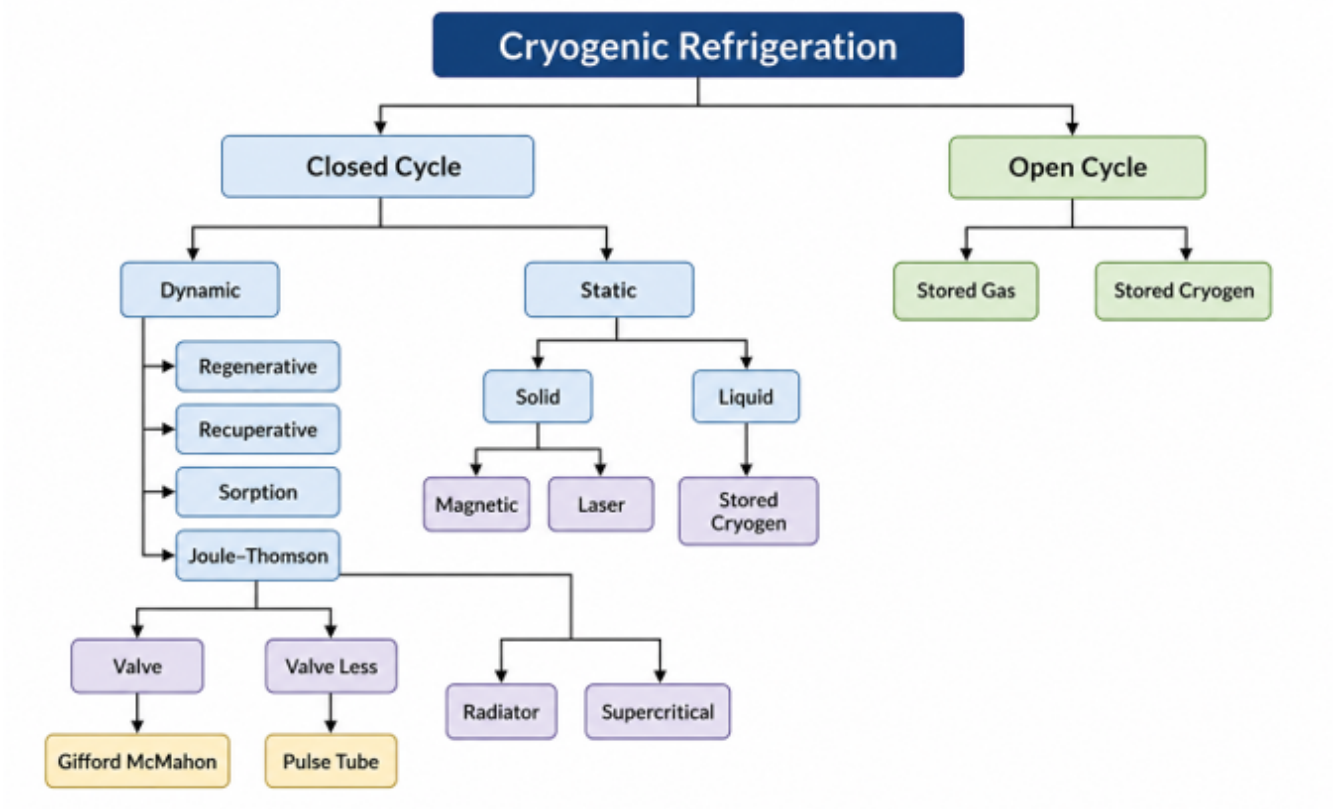


Fig 1. Classification of Cryocoolers [1]

3.3 Cryocoolers based on operating cycles

3.3.1. Open cycle cryocoolers

Open cycle cryocoolers are refrigeration systems that utilize cooling gases such as liquid helium or liquid nitrogen. These gases are allowed to flow openly into the cryocooler to achieve extremely low temperatures. This kind of cryocooler is very helpful in situations when samples or equipment need to be cooled quickly. In open cycle systems, a Joule-Thomson (J-T) cooler is often used, which operates by expanding a high-pressure gas stored at ambient temperature, resulting in refrigeration upon release to the atmosphere. The gaseous medium firstly undergoes a cooling process which is liquified and a makeup gas is supplied in a specific quantity which balances the liquefication rate. These type of cryocoolers include the expansion mechanism or working principle on boiling of cryogenics or Joule-Thomson expansion of highly pressurized gases. Open cycle cryocoolers are commonly employed in various fields, including infrared sensors for missiles, night vision devices and cryosurgical machines.

3.3.2. Closed cycle cryocoolers

Closed cycle cryocoolers, also known as dry cryostats, are refrigeration systems that cool devices down to cryogenic temperatures without the use of liquid cryogens. They are described as a cyclic process, with no inflow or outflow to the medium in the system. They function by the closed-loop compression and expansion of helium gas, enabling effective gas recycling. This kind of cryocooler is frequently used in conjunction with scientific equipment such as diffractometers and goniometers and

is especially beneficial for applications needing low-vibration settings. Closed cycle cryocoolers reject heat at extremely high temperatures and have a cooling effect at very low temperatures. In essence, they are mechanical cryocoolers. Cryocoolers with closed cycles include Stirling cryocoolers, Brayton cycle cryocoolers, Joule-Thomson cryocoolers, and others. These closed-cycle cryocoolers employ two working fluids: one is used directly to chill the region that needs to be cooled, and the other is used within the cycle.

3.3.3. Heat exchangers utilized in cryocoolers

An apparatus that transfers heat between two distinct fluid streams without mixing them is called a recuperative heat exchanger as shown in Figure 2. In recuperative heat exchangers, the two fluids- hot and cold, are separated by a continuous wall and across which heat transfer occurs. Heat can pass through the dividing barriers as each fluid has its own flow channel. This type of heat exchanger is highly efficient and is commonly used in power engineering to improve thermodynamic cycle efficiency, such as in gas turbine engines. Moreover, the cryocoolers can be identified from the Figure 3.

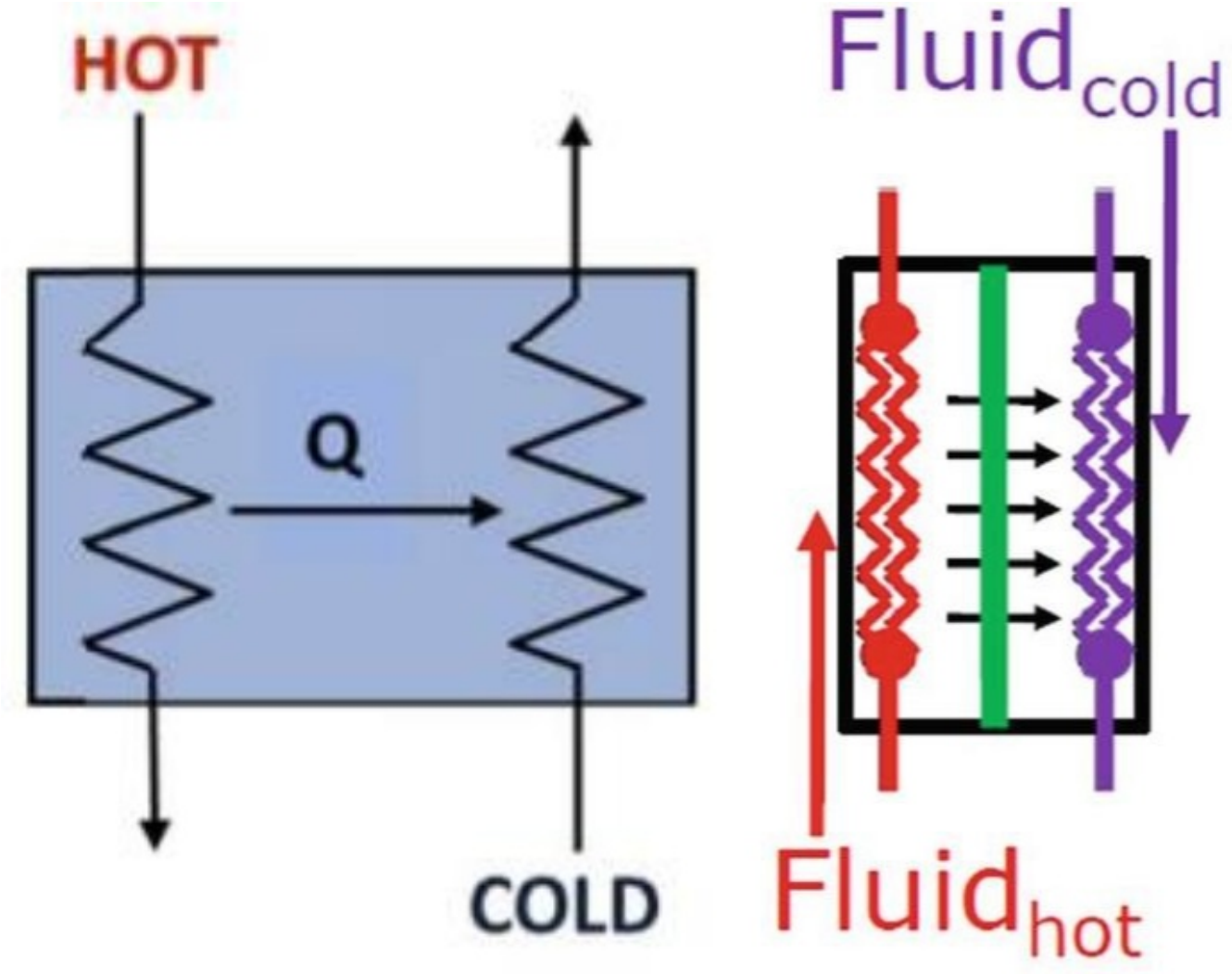


Fig 2. Schematic diagram of Recuperative Heat Exchanger [12]

In regenerative type heat exchangers, the flow of passage of hot and cold fluid is done through a singular flow stream that keeps on alternating. Before transferring heat from a hot fluid to a cool fluid, a regenerative heat exchanger stores the heat in a thermal storage medium. Heat is absorbed by the cold fluid as it comes into contact with the hot fluid and storage media. The two fluids may undergo external processing before flowing back through the heat exchanger for further processing. The process is usually cyclic or repetitive, with a matrix serving as an intermediate medium. The flow is an example of indirect heat

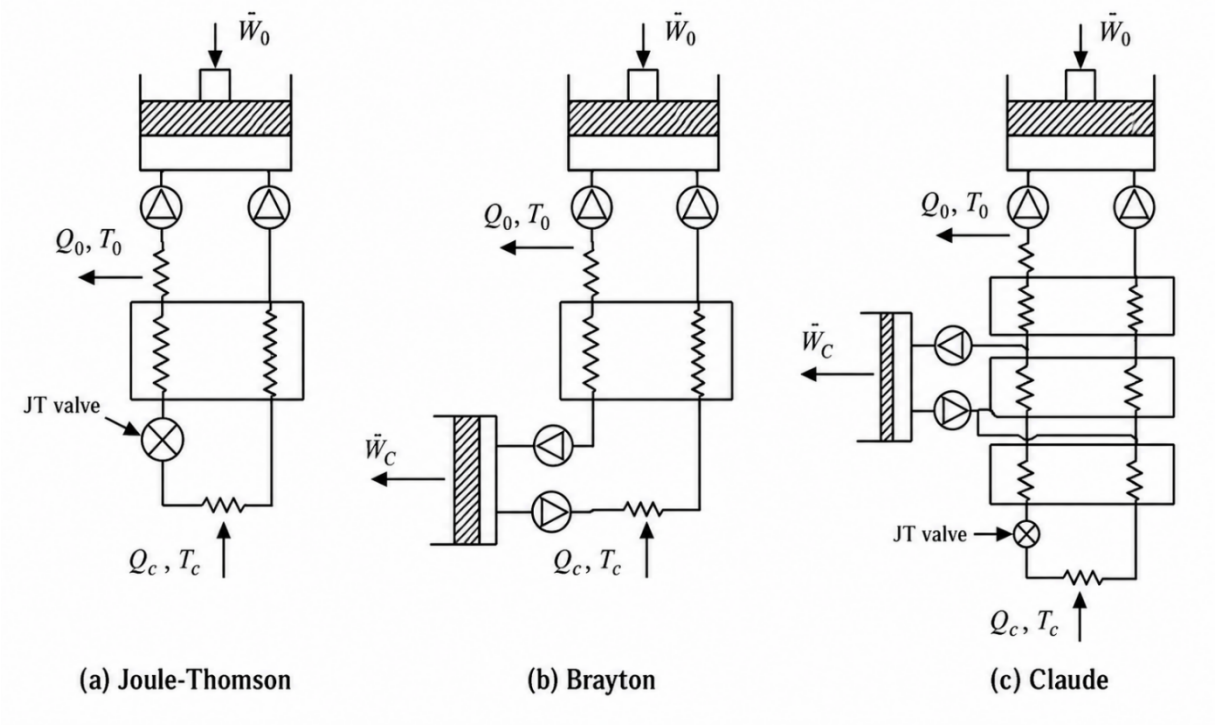


Fig 3. Recuperative type Cryocoolers [13]

transmission; it is periodic, alternating between the warm and cold fluids. Whereas, Figure 4, gives an idea of the regenerative type cryocoolers.

Crank-based compressors used in pulse tube cryocoolers provide high thermodynamic efficiency and reliable operation due to their simple design. However, they may produce significant noise and vibration and offer limited flexibility in varying cooling loads. These limitations can be minimized using vibration dampening techniques and variable speed drive technology for improved performance and adaptability.

3.4 Pulse Tube Refrigerators

Pulse tube cryocoolers can be classified in many approaches. It can be classified into two types on the basis of its pulse wave generation; they are Stirling type or GM type. By using rotary valves to switch between higher and lower pressure sources into the pulse tube and other components, GM type pulse tube cryocoolers disseminate pressure waves [1].

The piston cylinder assembly of the Stirling type pulse tube cryocooler is directly integrated with the hot end of the regenerator, allowing the piston's movement to directly create the pressure wave. The piston operates at high frequency and comprises of no valves like the GM type refrigerators as shown in Figure 5.

3.4.1. Basic Pulse Tube Refrigerators

The basic type of pulse tube cryocooler comprise of only the basic components of the cryocooler. It is composed of mainly these six components: - Compressor, Aftercooler, Regenerator, CHX, Pulse Tube and HHX. This type's primary benefit is its simplicity and ease of construction, which also results in less vibration at the cold point as shown in Figure 6(a). The most crucial element that influences the ultimate temperature gradient and the cryocooler's effectiveness is the phase angle between the mass flow rate and temperature.

3.4.2. Orifice Type Pulse Tube Refrigerators

This kind involves introducing a surge volume, or reservoir, to compensate for the temperature-to-mass flow rate phase discrepancy. The volume in the reservoir is controlled by not allowing the mass flow rate to change after the Hot heat exchanger and hence an orifice is introduced in series in the schematic after the HHX with the reservoir at the end as shown in Figure 6(b).

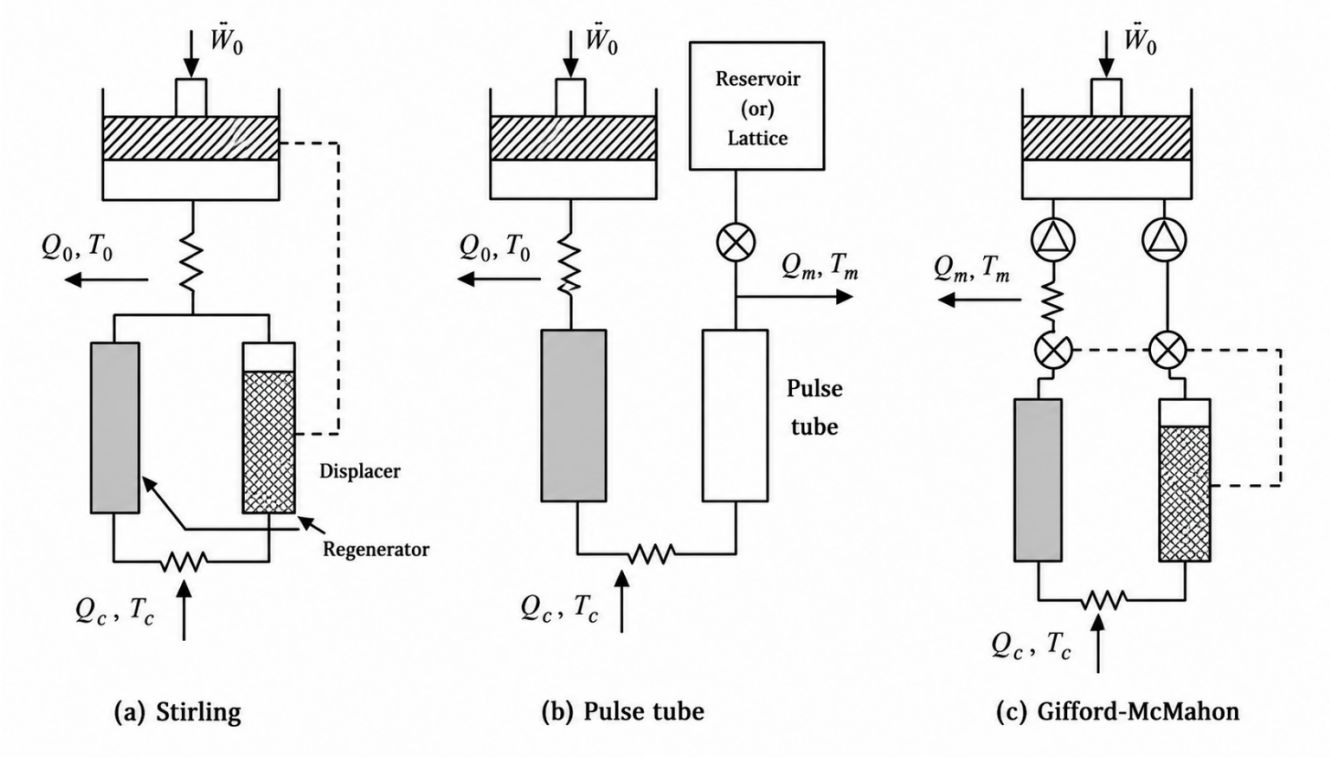


Fig 4. Regenerative Type Cryocoolers [13]

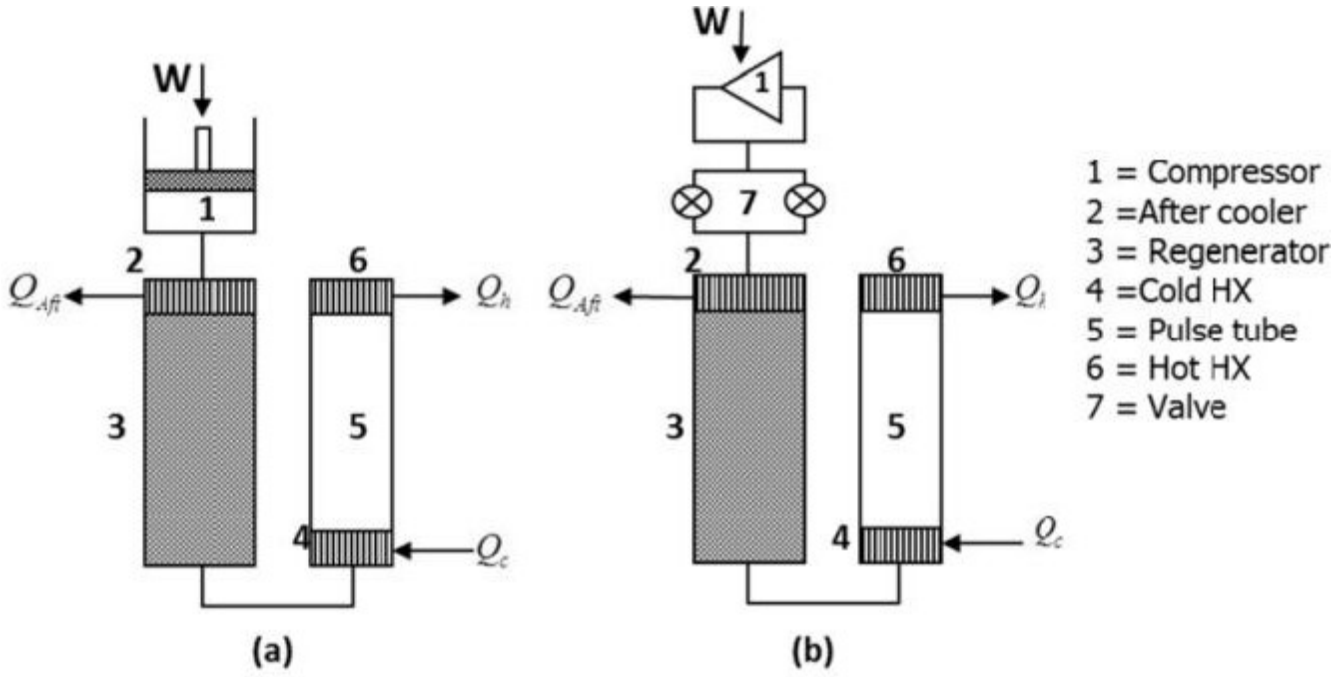


Fig 5. Schematics of basic PTC (a) Stirling type (b) G-M type [14]

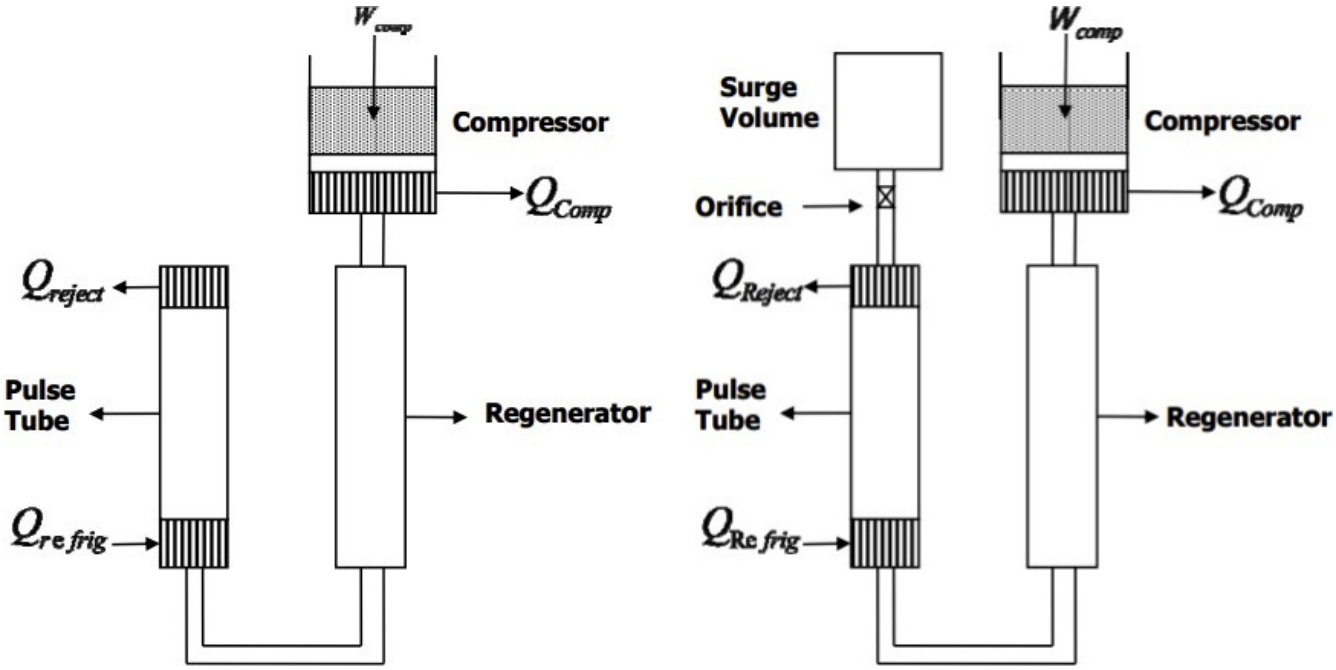


Fig 6. (a) Schematic of Basic Pulse Tube Cryocoolers[14]; (b) Schematic of Orifice type Pulse Tube Cryocoolers

3.4.3. Double Inlet Type Pulse Tube Refrigerators

Another set of orifice-type tubes with an optimally regulated aperture is introduced from the hot end of the pulse tube to the hot end (entrance) of the regenerator in order to counteract the losses in the regenerator. A portion of the gas can flow through the opening and directly enter the hot end of the pulse tube, avoiding the regenerator heat. This maintains the ambient warm temperature by forcing compressed air straight from the compressor towards the hot end of the pulse tube, increasing the temperature gradient and improving the cryocooler's performance. The volume of gas passing through the regenerator is decreased when the bypass flow is provided, which lowers the regenerator losses as shown in Figure 7.

3.4.4. Inertance Type Pulse Tube Refrigerators

The pulse tube cryocooler's performance is mostly dependent on the phase difference between temperature and mass flow rate. The series of the assembly from the hot heat exchanger is linked to another hollow, thin tube known as the inertance tube, just like the displacer is replaced with a hollow tube for a phase shift. The inertance tube adds reactive impedance to the system and this phenomenon generates the phase shift between the mass flow rate and the temperature and produces an improved enthalpy flow as shown in Figure 8.

3.4.5. Linear Type Pulse Tube Refrigerators

As the name implies, a linear or inline type pulse tube refrigerator has the entire system arranged in a straight line, from the regenerator to the reservoir. When a high performance cryocooler is needed, this PTC arrangement is frequently taken into consideration since the fluid flow path losses are minimal and there are no curves in the system. This arrangement has a drawback in that accessing the cold temperature advantage is challenging and takes more room, despite the extremely high performance attained. The ideal setup for this configuration is one in which the tube's hot end is placed within the vacuum chamber.

3.4.6. U-shape type Pulse Tube Refrigerators

This kind of arrangement is intended for a small-sized cold head assembly. The heat sink, the regenerator's cold end, and the pulse tube are bent downward. The vacuum chamber is where the hot ends of the regenerator and pulse tube are fixed. Although the performance is not as appealing as the inline assembly, the access to the cold point is much easier and the losses from the extraction is bare minimum. The cold heat exchanger is at the lowest bend point making the assembly not only compact but easier to access for the cold point.

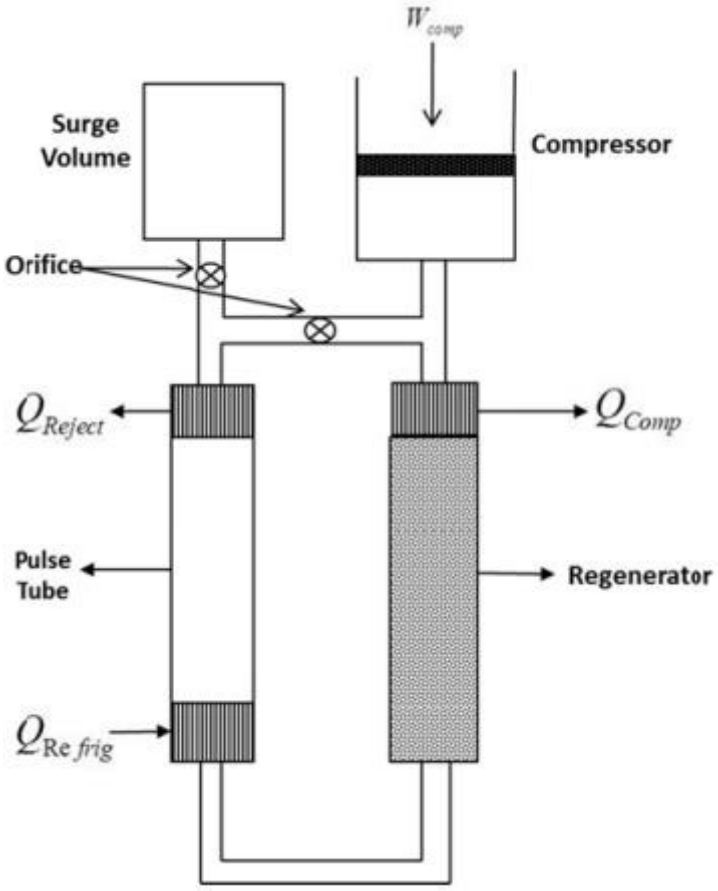


Fig 7. Schematic of Double Inlet type Pulse Tube Cryocoolers[14]

3.4.7. Coaxial Pulse Tube Refrigerators

To resolve the issues arising from the linear and U shape PTC of having a compact yet high performance result, the other set of geometry known as coaxial type is used. Although the performance is hampered because of the degradation in regenerator losses, the major limitation is the presence of heat transfer from the regenerator to the pulse tube. A small layer of insulating material must be placed between the regenerator and the pulse tube because the temperature gradient that forms should be different from the ends of both the regenerator and the pulse tube. The regenerator's and the pulse tube's combined diameter is raised, but the system's total length is much shorter than it would be in an inline installation.

3.4.8. Annular Pulse Tube Refrigerators

In an annular type pulse tube cryocooler, the regenerator is stored inside the pulse tube rather than surrounding it in the form of a disc. The regenerator and pulse tube are once more separated by a thermally insulated wall. All categories can be depicted from the Figure 9.

Applications for pulse tube cryocoolers range from superconducting electronics to chilling infrared sensors. These cryocoolers operate by using a compressor to compress and expand a gas, creating a temperature difference that is then used to cool a target object. One type of compressor used in pulse tube cryocoolers is the cam and follower mechanism. In this essay, we will explore the working principle, advantages, and challenges of using a cam and follower-based compressor in pulse tube cryocoolers.

In order to cool the target item, pulse tube cryocoolers work by compressing and expanding a gas-typically helium-using a compressor. This creates a temperature differential. A particular kind of compressor is the cam and follower mechanism, which compresses gas by using a revolving cam to drive a follower. Because of its great efficiency, little noise and vibration, and low maintenance needs, the cam and follower mechanism are chosen over other compressor types. The cam and follower

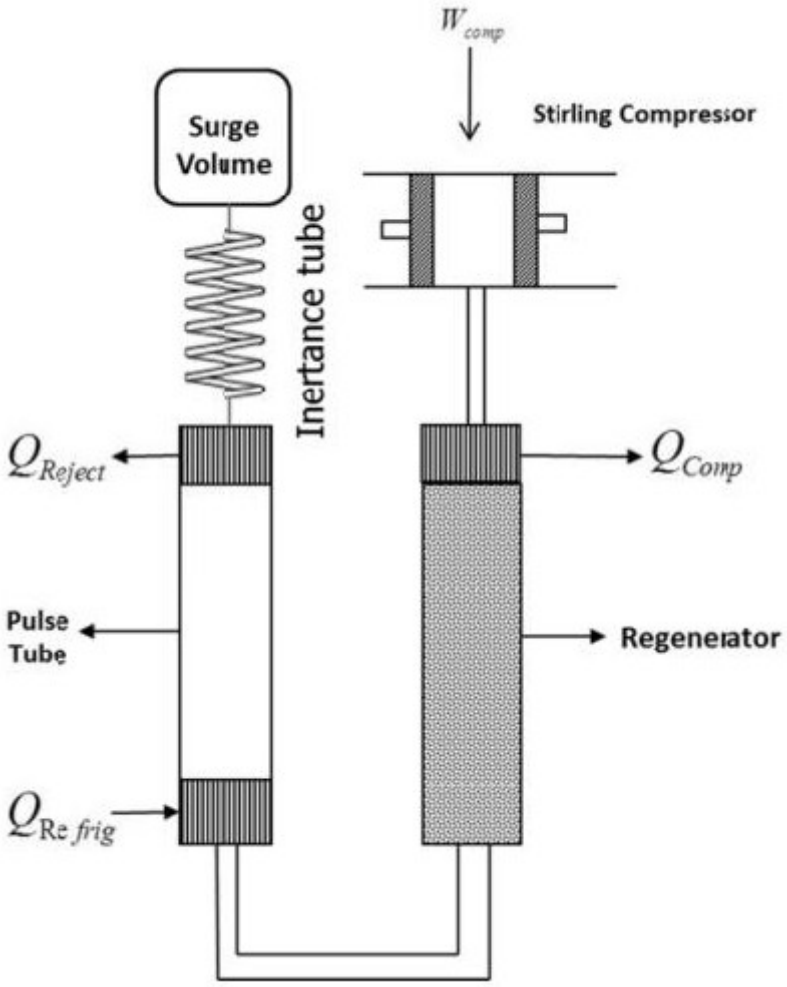


Fig 8. Schematic of Inertance type Pulse Tube Cryocoolers [14]

mechanism consist of a cam, which is a rotating disk with an irregular shape, and a follower, which is a sliding mechanism that follows the cam's shape. As the cam rotates, the follower is pushed up down, compressing and expanding the gas in the pulse tube. The target item is cooled by the temperature differential produced by the gas's compression and expansion.

A high-frequency pressure wave is used by pulse tube cryocoolers (PTCs), a form of cryogenic refrigerator, to move heat from a colder area to a warmer one [16]. They consist of two main parts: the linear compressor and the cold head. The linear compressor generates the high-frequency pressure wave, and cooling occurs at the cold head [17]. PTCs have been considered a promising candidate for cooling high- temperature superconducting (HTS) devices.

3.4.8.1. Novelty of the Present Review. The novelty of this review paper lies in the comprehensive integration of pulse tube cryocooler technologies with detailed insights into cam and follower-based compressor mechanisms, which are comparatively less explored in existing review studies. Unlike conventional review papers that primarily focus on cryocooler thermodynamics or phase shift mechanisms, the present work establishes a direct relationship between compressor design, pulse tube configuration, and overall cryogenic performance. The review systematically compares different pulse tube refrigerator geometries and phase-shift techniques while highlighting the influence of compressor dynamics on efficiency, vibration characteristics, compactness, and reliability. Additionally, the paper provides a unified discussion on recent developments in inertance-type and low-vibration pulse tube cryocoolers for advanced industrial and space applications. The study also identifies critical research gaps related to regenerator materials, heat exchanger optimization, phase synchronization, and compact compressor design, thereby offering future research directions for the development of high-performance and energy-efficient cryogenic refrigeration systems.

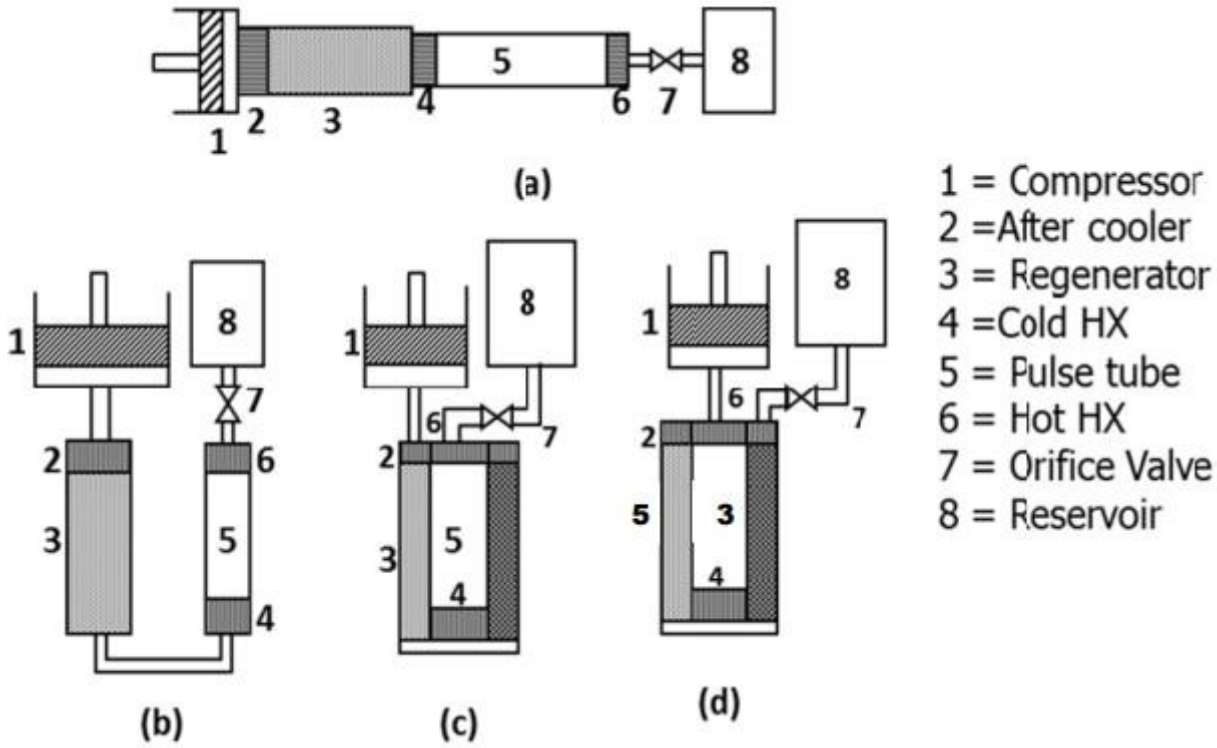


Fig 9. Schematic diagram of pulse tube geometry (a) Linear, (b) U-tyoe, (c) Coaxial, and, (d) Annular [15]

4 Related studies, advancement in design and performance

Cam and Follower-Based Compressors are a type of linear compressor that can be used in PTCs [18]. Their method of operation involves creating the high-frequency pressure wave required for cooling utilizing a piston fastened to a cam-follower [19]. Cam and follower-based compressors have several advantages over other linear compressor designs, such as high efficiency, oil-free operation, low cost, and compact design. Furthermore, they don't have a crank mechanism, which makes them more reliable and less prone to wear and tear than conventional reciprocating compressors [20].

Using Cam and follower-based compressors in PTCs has several advantages. Firstly, they have a higher volumetric efficiency compared to other types of linear compressors, such as scroll compressors. This is because of their reduced clearance volume, which enhances thermodynamic performance and leads to a larger compression ratio [21]. Furthermore, compared to other compressor types, Cam and Follower based compressors are less maintenance-intensive and more dependable, making them an affordable choice for PTCs [22]. Lastly, because of their small size, they are perfect for use in applications that need portability and limited space [23]. Overall, the use of Cam and Follower based compressors in PTCs offers several advantages and can lead to improved performance and cost-effectiveness.

4.1 Design and working principle of a cam and follower-based compressor in a pulse tube cryocooler

The compressor that is part of a pulse tube cryocooler is called a Cam and Follower based compressor. It consists of a linear compressor and a cold finger. The linear compressor transforms acoustic power into electrical power, which powers the pulse tube cryocooler. Refrigeration has long been a commercial application for reciprocating compressors, which are powered by induction motors using a crank mechanism. Recently, a novel type of PZT-based compressor operating at mechanical resonance was developed for Stirling-type cryocoolers driven by pneumatics. The usual parts of a cam and follower-based compressor in a pulse tube cryocooler are an intake and exhaust valve, a cylinder or housing, a piston or diaphragm, a crankshaft or connecting rod.

A compressor using a cam and follower system compresses a gas during the intake stroke and releases it during the exhaust stroke in a pulse tube cryocooler [24]. When the piston descends during the intake stroke, a vacuum is created that pulls gas into

the cylinder. During the compression stroke, the exhaust valve forces the compressed gas out of the cylinder as the piston rises. After being compressed, the gas is sent to the pulse tube, where it experiences several compressions and expansions to provide cooling effects. The kind of gas being compressed, the geometry of the compressor, and other factors all affect the performance of a cam and follower-based compressor.

Achieving high efficiency, dependability, and little vibration are important design factors for a compressor in a pulse tube cryocooler that is based on a cam and follower. The compressor size is determined by the pulse tube cold finger performance parameters[25]. The design of the compressor must consider the gas flow rate, pressure, and temperature in addition to the mechanical stresses and strains it will experience during operation.

4.2 Performance and applications of cam and follower-based compressors in pulse tube cryocoolers

Because of their better performance features, compressors based on cams and followers are being employed in pulse tube cryocoolers more and more. Stirling-type cryocoolers are frequently powered by linear compressors, and the acoustic power of the compressor has a direct effect on the cryocooler's performance. Theoretical calculations have been corroborated by experiments on pulse tube cryocoolers with linear compressors, and a novel efficiency map based on the cryocooler's overall efficiency has been presented[20]. Additionally, high-efficiency, low-frequency linear compressors have been proposed for Gifford-McMahon-type cryocoolers based on experimental data obtained from commercial pulse tube cryocoolers[22]. However, in pulse tube cryocoolers, it has been discovered that cam and follower-based compressors are more dependable and efficient than linear compressors. These compressors' crank mechanism transforms rotational action into linear motion, which ineluctably results in friction loss that must be reduced by the use of oil.

5 Discussion

The overall review demonstrates that pulse tube cryocoolers have undergone remarkable advancements over the past few decades owing to their ability to achieve cryogenic temperatures with fewer moving components and reduced maintenance requirements. The absence of mechanical moving parts at the cold end significantly improves operational reliability and minimizes vibration, making these systems highly suitable for precision applications such as infrared imaging, superconducting electronics, aerospace instrumentation, and medical diagnostics. The reviewed studies indicate that the cooling performance of pulse tube cryocoolers is strongly dependent on the optimization of phase shift mechanisms, regenerator effectiveness, compressor efficiency, and pulse tube geometry. Among the various configurations, inertance-type and double inlet pulse tube cryocoolers have demonstrated superior thermodynamic performance due to improved phase control and enhanced enthalpy flow characteristics.

The review further reveals that cam and follower-based compressors provide an attractive alternative to conventional linear compressors because of their compact structure, oil-free operation, improved volumetric efficiency, and lower maintenance requirements. However, challenges associated with vibration, noise generation, thermal losses, and phase synchronization still limit the widespread commercial implementation of these systems. Researchers have proposed several strategies such as advanced regenerator materials, optimized heat exchanger geometries, variable speed control systems, and active phase shift mechanisms to overcome these limitations. Moreover, the development of compact and lightweight cryocoolers for portable and space-based applications continues to drive innovation in compressor design and system integration. Overall, the reviewed literature confirms that pulse tube cryocoolers possess significant potential for future cryogenic applications, although further experimental and numerical investigations are essential for improving system efficiency, durability, and environmental sustainability.

6 Conclusion

The present review provides a comprehensive and updated assessment of recent advancements in pulse tube cryocooler (PTC) technologies with particular emphasis on compressor systems, phase-shift mechanisms, regenerator optimization, and thermodynamic performance enhancement techniques reported during 2020–2026. The study critically compared different pulse tube configurations including basic, orifice, inertance, double-inlet, coaxial, annular, Stirling-type, and Gifford–McMahon-type cryocoolers using key performance parameters such as cooling temperature, cooling capacity, coefficient of performance, pressure ratio, vibration characteristics, and operational stability. The comparative analysis revealed that inertance-type and double-inlet pulse tube cryocoolers offer significantly improved phase synchronization and approximately 15–25% higher thermodynamic efficiency compared with conventional pulse tube systems. Similarly, recent gas-bearing and

moving-coil compressor technologies demonstrated nearly 30–40% reduction in vibration levels, thereby improving their suitability for aerospace, superconducting, and precision cryogenic applications.

One of the major novelties of the present review lies in establishing a direct relationship between pulse tube configurations, compressor dynamics, phase-shift mechanisms, and overall cryogenic performance within a unified comparative framework. Unlike earlier reviews that primarily focused on general thermodynamic principles, the present study integrates recent technological developments such as active phase-shift control systems, AI-assisted optimization, additive manufacturing techniques, miniature cryocoolers, and low-vibration compressor technologies. The review additionally highlights commercialization barriers, manufacturing limitations, regenerator inefficiencies, thermal leakage issues, synchronization instability, and acoustic losses that continue to restrict ultra-low-temperature operation and large-scale industrial implementation of advanced pulse tube cryocoolers.

The review findings indicate that future research should focus on the development of compact and energy-efficient cryocoolers with improved regenerator materials, advanced heat exchanger geometries, and optimized compressor designs capable of minimizing vibration and thermal losses. Greater emphasis should also be placed on AI-based performance optimization, smart cryogenic control systems, additive manufacturing of compact cryogenic components, and hybrid phase-shift mechanisms to improve operational stability and cooling efficiency. Furthermore, long-term experimental validation, reliability assessment under extreme operating conditions, and cost-effective manufacturing strategies are essential for accelerating commercialization of pulse tube cryocoolers in aerospace, medical, quantum computing, and superconducting applications.

Despite providing a comprehensive comparative assessment, the present review has certain limitations. The analysis is primarily based on peer-reviewed studies published between 2020 and 2026, and some proprietary industrial developments may not have been publicly available. In addition, variations in operating conditions, experimental setups, and reporting methodologies among different studies may influence direct performance comparisons. Nevertheless, the present review offers a clear technological roadmap and valuable scientific insights for researchers, designers, and industrial practitioners working toward the development of next-generation high-efficiency pulse tube cryocoolers.

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