

Review paper on Design and Development of Miniature Moving Magnet Pulse Tube Cryocooler

Jitendra G. Shinde^{1*}, M. M. Khot²

Abstract

Developing a miniature moving magnet pulse tube cryocooler to address the limitations in existing cryocooler technologies, especially in terms of compactness, lightweight design, durability, and maintenance-free operation, aligns with the demands of modern applications, particularly in space and similar environments. Integrating a miniature compressor and motor is essential for the functionality of the cryocooler. The design should prioritize efficiency and reliability while addressing challenges related to vibrations and maintenance commonly associated with traditional cryocooler systems. The use of a pulse tube and regenerator in your proposed design is promising, as these elements can enhance the cooling and overall performance of the cryocooler. Furthermore, the inclusion of magnetic components can reduce the number of moving parts, thereby decreasing vibrations, maintenance needs, and system complexity, ultimately enhancing the reliability and operational lifespan of the cryocooler. Considering the selection of suitable materials, such as for the regenerator and pulse tube, and optimizing the thermodynamic processes to efficiently achieve the desired low temperatures will be crucial as you progress with your development. Proposed approach to design and develop a miniature moving magnet pulse tube cryocooler aligns with the industry's push for compact, efficient, and reliable cooling solutions. It has the potential to open up new opportunities in various applications, including space.

Keywords: Design, compressor, motor, cryocooler, pulse tube, regenerator.

INTRODUCTION

The escalating demand for cryogenic temperatures in research and technological advancements has prompted rapid development in cryocooler technology. The need for efficiency, reliability, cost-effectiveness, and longevity in cryocoolers has been a driving force behind this progress. While Stirling cryocoolers have been widely used to meet these requirements, their mean failure time of 4000 hours has limited their application in satellites and most commercial uses. However, the potential research and development of miniature moving magnet pulse tube cryocoolers presents a promising solution to this reliability issue. Pulse tube cryocoolers have garnered significant attention due to their advantages in reliability and reduced cold head vibrations compared to other regenerative cryocoolers.[21] Their

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mechanical simplicity, high reliability, long maintenance-free, low specific power consumption, small size, low weight, and reduced vibration levels make them attractive for various applications, particularly in space. The potential to achieve higher efficiency with the development of miniature moving magnet pulse tube cryocoolers makes them increasingly sought after, especially in space applications. Their performance in terms of cooling power, cooling temperature, and efficiency achievable, and their lack of moving parts at the cold section positions them favorably compared to other

small cryocoolers, given their reliability, simpler construction, and lower vibration levels.[22] The development of a moving magnet linear motor type pulse tube cryocooler the opportunity for a more compact design with the potential for higher efficiency. The use of a novel low-cost moving magnet linear motor, with transverse flux paths between the static part and the moving magnet assembly, offers a cost-effective alternative to existing moving coil compressors. This motor design, with its simple and robust moving magnet assembly, low moving mass, and efficient magnet utilization, enables the achievement of high efficiencies while keeping resistive and core losses low.[23]

Furthermore, the cooling process of pulse tube cryocoolers, achieved the adiabatic expansion of a gas piston controlled by an orifice valve, is enhanced by directly attaching the compressor piston to the moving magnet assembly, ensuring reciprocal movement at the same frequency.[24] The integration of these advancements in the development of miniature moving magnet pulse tube cryocoolers holds great promise for meeting the increasing demands for efficient and reliable cryocooling systems, particularly in space applications.[25]

LITERATURE REVIEW

It's understandable that numerous researchers have contributed to the advancement of pulse tube cryocoolers using various methods. Due to the extensive volume of work in this field, it's not feasible to mention every research endeavor. However, I can focus on highlighting the most influential and motivational work that has significantly contributed to the progression of this technology. If you have specific research or work that you would like to discuss or elaborate on, please feel free to provide more details, and I can certainly offer assistance tailored to your requirements. It can be categorized as :

Cryocooler Development and Design

scholars delve into diverse facets of cryocooler technology, encompassing the scrutiny and enhancement of moving magnet linear compressors, the formulation of valved linear compressors tailored to precise thermal conditions, the engineering of compressors catered to miniature pulse tube cryocoolers, and the detailed exposition of particular cryocooler .

Ming Xia and Xiaoping [01] The analysis of the resonant frequency of the moving magnet linear compressor in a Stirling cryocooler reveals key factors influencing its performance. The study addresses the need for high reliability and cost-effective coolers for high-performance IR detectors. The moving magnet linear compressor, in conjunction with flexure spring, is identified as a promising solution due to its potential to achieve a Mean Time to Failure (MTTF) of up to 20,000 hours, surpassing the current MTTF of 8000 hours for tactical linear coolers. The paper discusses the force balance relationship in the linear compressor, considering forces from friction, springs, pressure differentials, and electric forces resulting from applied current. The resonant frequency of the linear compressor is crucial, and its analysis involves factors such as magnet spring stiffness, machine spring stiffness, and gas spring stiffness. Computational fluid dynamics (CFD) and finite element method (FEM) simulations are employed to analyze the gas spring, providing insights into the flow and heat transfer processes within the cryocooler. The results of the simulations demonstrate pressure and temperature distributions, offering valuable information for understanding the behavior of the cryocooler. The findings from the analysis contribute to a deeper understanding of the resonant frequency of moving magnet linear compressors in Stirling cryocoolers, providing essential knowledge for the design and optimization of cryocoolers in practical applications, particularly in the development of high-performance IR detectors and related technologies.

W. W. Wang et al. [02] the development of a valved moving magnet linear compressor for a Joule-Thomson cryocooler is outlined with a primary emphasis on achieving high efficiency within the temperature range of 4-6 K. The design objectives, as summarized in Table 1, encompass critical parameters such as input power, pressure ratio, efficiency, resonant frequency, lifetime, and swept volume. The choice of a linear motor is based on its advantageous features, including enhanced

efficiency, greater specific electromagnetic force, absence of flying leads, and a compact structure. Key components of the motor, such as outer yokes, inner yokes, winding coil, coil holder, permanent magnets, and fixed rings, play integral roles in generating the reciprocating force needed to drive the piston. This force is produced through the application of AC current to the coil. The air gap resistance is meticulously characterized using the equivalent magnetic circuit method.

Careful attention is given to the design of flexure springs to ensure appropriate axial and radial stiffness, along with a stress distribution that falls within a safety margin. The dynamic model of the linear compressor is presented, and its operational characteristics are elucidated through two equations. Optimal power consumption is achieved when the motor operates under resonance conditions. Graphs depicting the amplitudes of voltage and displacement under varying frequencies when the compressor is excited by constant current are provided. The valved moving magnet linear compressor demonstrates notable performance in achieving a relatively high-pressure ratio for Joule-Thomson cryocoolers. The potential applications of this designed linear compressor extend to tactical and space applications, contributing significantly to the advancement of cryogenics technology.

M. Mai et al. [03] The development of the Miniature Flexure Bearing Cryocooler SF070, with a specific emphasis on elevating reliability and curbing the overall cost of ownership for infrared (IR) devices. The incorporation of Flexure Bearing technology in linear coolers proves instrumental, yielding a Mean Time To Failure (MTTF) exceeding 20,000 hours—a marked enhancement in durability. Engineered to function seamlessly with an 8 mm Stirling cold finger in a sleeve design, the SF070 cryocooler boasts advantages such as heightened reliability, extended operational lifespan, and diminished total cost of ownership for IR devices. Through a comparative evaluation against the SF100, the SF070 showcases superior performance and adherence to specified form factor requirements. The developmental aim for the SF070 was to either match or surpass the performance benchmarks set by the SL070 while maintaining consistent outer dimensions. Despite potential drawbacks, including diminished power factor and additional iron losses in comparison to the SL070, the SF070 achieves an overall enhancement in motor efficiency.

This research addresses challenges encountered during the transfer of Flexure Bearing technology to smaller form factor devices. It places emphasis on mitigating moving magnet specific losses and comprehending the influence of operating frequency on the maximum attainable power factor and iron losses. Notwithstanding these challenges, the SF070 emerges as a compressor with an equivalent diameter and even reduced length compared to its predecessor, the SL070. In conclusion, this paper provides an exhaustive overview of design considerations, performance metrics, and challenges associated with the Miniature Flexure Bearing Cryocooler SF070. The results underscore its potential to significantly elevate reliability and reduce the total cost of ownership for IR devices.

Kun Liang et al. [04] The analysis presents a comprehensive examination of a moving magnet linear compressor, providing valuable insights into its performance and characteristics. The study incorporates experimental evaluation, mathematical modeling, and comparative analyses, with the overarching objective of optimizing the design and identifying critical parameters influencing system transients.

The document meticulously details the moving magnet linear compressor, with a specific focus on its losses and efficiency. A comprehensive schematic illustrates various compressor losses, encompassing copper loss, core loss, additional eddy current loss, seal leakage loss, heat transfer, and pressure drop loss. Calculations of net power and shaft power at the design point reveal a close correlation between the two. The study identifies copper loss as a significant factor contributing to reduced compressor efficiency, while also analyzing pressure drop loss and heat transfer loss.

Performance measurements of the compressor are conducted through a robust mathematical model, accounting for forces in the system, including motor force, spring force, cylinder gas pressure force,

drive case gas pressure force, and damping force. The model facilitates the calculation of internal energy change and heat transfer between the compressed gas and the cylinder wall, providing valuable insights into the compressor's behavior during operation.

In summary, the study offers a profound understanding of the moving magnet linear compressor's behavior, establishing a foundation for optimizing its design and performance. The findings contribute to the potential enhancement of efficiency and effectiveness in this type of compressor, thereby advancing the field of linear compressor technology.

Rühlich I et al. [05] The development of the Miniature Moving Magnet Cryocooler SX040 is comprehensively outlined in this report, focusing on fulfilling specific cooling capacity and efficiency criteria for high-performance cooled IR systems. The cryocooler integrates an exceptionally efficient dual-piston Moving Magnet driving mechanism, resulting in a compact compressor measuring less than 100mm in length. Utilizing cutting-edge simulation technology, the authors accurately modeled the cryocooler's thermodynamics and magnetic behavior. The optimization process included fine-tuning the compressor's stroke capabilities to minimize piston forces, current magnitude, and copper losses. Magnetic interactions were also enhanced by tailoring geometrics and utilizing suitable magnetic materials for the desired operation envelope. Given its intended use in 24/7 applications, reliability is a paramount consideration for the cryocooler. To ensure this, the driving mechanism incorporates moving magnet technology, with coils isolated from the helium vessel to mitigate contamination risks. Cost-effectiveness was achieved by transitioning from thread-based joining to automated welding procedures. Additionally, an integral expander design, featuring a versatile thermoplastic material serving as both the bearing surface and regenerator housing, contributed to overall cost reduction. In summary, the Miniature Moving Magnet Cryocooler SX040 represents a compact, efficient, and reliable solution tailored for high-performance cooled IR systems. Its design facilitates the utilization of high operation temperature (HOT) FPAs, ultimately reducing Size, Weight, and Power (SWaP) and enhancing the overall performance of the system.

Magnet Ring Motor

Design: In the field of Magnet Ring Motor Design, researchers explore innovative techniques using segmented magnets to construct magnet rings, conducting thorough testing across diverse operational parameters to evaluate and optimize motor performance for various applications.

R. Karunanithi et al. [06] The utilization of eight radially magnetized segmented magnets to form one set of a magnet ring, combined with the construction of four such magnet rings, constitutes a noteworthy approach to motor design. The testing of the motor using a variable voltage and variable frequency power supply, capable of driving 140 watts of load, allows for a thorough assessment of the motor's performance under varying operational parameters. This testing regime provides essential data on the motor's response to different power inputs, contributing to a comprehensive understanding of its operational characteristics. Overall, the design, fabrication, and testing of this moving magnet type linear motor for a pulse tube cryocooler represent a significant contribution to the ongoing advancements in cryocooler technology for ground applications. The thorough and methodical approach taken in each phase of the motor's development and validation underlines the potential for meaningful impact within the field of cryocooler technology.

Compact Coaxial Pulse Tube Cryocooler

The development of advanced cryogenic cooling systems, particularly examining the compact coaxial pulse tube design for efficient and low-noise cooling of infrared detectors, adhering to stringent dimensional constraints and performance specifications.

H.Z. Dang et al. [07] The study focuses on the development of a compact coaxial pulse tube cryocooler (PTC) designed to provide reliable and low-noise cooling for an infrared detector, with the

specific objective of serving as a direct substitute for an existing Stirling cryocooler while adhering to specified dewar dimensions. To address the challenges posed by the miniature structure, the design and optimization strategy involves employing an increased operating frequency and elevated average filling pressure to compensate for the reduced working gas volume.

For performance prediction and optimization, a computer simulation model is established using a finite difference method to solve conservation equations for mass, energy, and momentum. Simultaneous optimization of geometrical and operating parameters is conducted to maximize the Coefficient of Performance (COP) and/or cooling capacity. The PTC incorporates a dual opposed moving magnet compressor based on technology developed at the Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS). Notably, the motor coil is positioned outside the working gas space, eliminating coil epoxy and electrical feed-throughs within the working gas space, resulting in a lightweight, highly efficient, and low-contamination system.

The inheritance tube serves as the exclusive phase-shifting mechanism in the PTC, albeit with limitations on the system's phase-shifting ability due to its miniature dimensions. Nevertheless, the PTC is poised to seamlessly replace specific Stirling cryocoolers within designated dewar constraints and may even serve as an alternative to J-T cryocoolers in specialized applications requiring rapid cooldown. The adoption of this miniature PTC is anticipated to offer benefits such as improved efficiency and reduced contamination, contributing to advancements in cryocooling technology for infrared detectors.

Micro-Miniature Stirling Cryocoolers

X. P. Chen et al. [08] The research focuses on the advancement of micro-miniature Stirling cryocoolers tailored for high-temperature applications, in line with the Size, Weight, and Power (SWaP) concept, which advocates for the reduction of cooler dimensions, weight, and power consumption. This trend is particularly pertinent for the 3rd generation Mercury Cadmium Telluride (MCT) focal plane arrays, aiming to operate at higher temperatures without compromising performance compared to traditional 77K systems. This necessity propels the development of High Operating Temperature (HOT) MCT detectors, where the operating temperature primarily influences thermal-induced free carriers and noise, while parameters like cut-off wavelength and sensitivity remain unaffected. The paper systematically compares micro-miniature Stirling cryocoolers with their miniature counterparts in terms of size, weight, and power. The innovative design features a compact linear compressor, such as a 30 mm diameter and 60 mm length for the opposed piston compressor or a 40 mm length for the single piston compressor. A rotary cooler designed for HOT applications achieves rapid cooldown in 3-4 minutes through a booster, offering a viable alternative for SWaP-efficient thermal imaging systems. Additionally, the paper delves into the application of miniature Stirling cryocoolers in infrared detector assemblies, emphasizing the critical importance of miniaturization and optimization to enhance their overall performance. Factors influencing cooling capacity, such as the swept volume of the compressor, charging pressure, cold-end temperature, and regenerator thermal conductivity, are carefully examined. In conclusion, the study positions micro-miniature Stirling cryocoolers as a promising technology for high-temperature applications, with potential uses in thermal imaging systems, medical imaging, and environmental monitoring. This technology aligns well with the SWaP concept, offering compact and efficient cooling solutions for a variety of contemporary applications.

Miniature Pulse Tube Cryocooler

Veprík et al. [09] the development of a microminiature linear split Stirling cryogenic cooler, specifically designed for portable infrared (IR) applications, with a particular emphasis on military and antiterrorist operations. It highlights the distinct advantages of linearly driven cryogenic coolers, such as enhanced system design flexibility, longer operational lifetime, reduced exported vibration, and aural stealth, in comparison to their rotary-driven counterparts. Recent technological advancements in high-temperature IR detectors have prompted the development of microminiature cryogenic coolers, both

rotary and linear, with a specific focus on the suitability of linear coolers for these applications. The report provides an overview of the Ricor model K527 microminiature split Stirling linear cryogenic cooler, tailor-made for portable infrared imagers. Theoretical analysis is discussed, emphasizing the selection of supporting spring stiffness and optimal motor design. Environmental considerations for portable hand-held imagers guide the rejection of a "contactless" approach in favor of a hardened and polished steel design. The pilot cryocooler's performance is reported to be smaller, lighter, and exhibits improved noise and vibration signatures compared to similar integral rotary coolers. Concludes by summarizing the project status, indicating that the pilot cryocooler has accumulated approximately 3000 hours of irregular operating profiles and is scheduled for qualification testing by the end of 2006.

N. Matsumoto et al. [10] delineates the development of a compressor tailored for a miniature pulse tube cryocooler with a heat lift of 2.5 W at 65 K. Employing a moving magnet motor known for its superior compactness and efficiency compared to traditional moving coil motors, the motor design integrates a permanent magnet and two side magnets to establish a stable state at the center of each leg of an outer yoke. The generative force is explained using Fleming's left-hand rule and an equivalent current for generative force. The compressor achieves a total compression work of 75 W with 90% efficiency, demonstrating a lifespan exceeding 50,000 hours.

The designated application for the cryocooler is the cooling of high-temperature superconductive devices utilized in wireless telecommunication systems. The paper also provides a detailed account of the development of the cryocooler's magnetic circuit for element tests, accompanied by various approaches for bearing support magnets. Simulation results indicate that, without supplying current to an exciting coil, the magnetic flux forms a loop between a magnet and the leg of an outer yoke, creating an axially stable state. Upon applying a current of 1.6 A, the magnetic flux traverses the entire outer yoke, concentrating at the bottom side of each leg and generating a force in the opposite direction. In summary, the paper delivers valuable insights into the development of a high-performance cryocooler suitable for commercial applications, showcasing potential applications across various fields.

Design and Development of Cryocoolers

Y. Hiratsuka and Y. M. Kang [11] the development of a prototype Stirling pulse tube cryocooler, engineered to provide a cooling capacity ranging from 1 to 5W at 80K. Pulse tube cryocoolers are favored for their reliability, straightforward construction, and minimal vibration levels, distinguishing them from other small cryocoolers. Operating on the principle of adiabatic expansion of a gas piston, the cryocooler utilizes a gas piston with a controlled and optimized phase angle through an orifice valve. The paper meticulously outlines the design and development of the cryocooler, incorporating a numerical analysis model to optimize cycle efficiency. The prototype features a split Stirling type double inlet pulse tube with opposed pistons driven by a linear motor. The compressor is available in two sizes, each with distinct swept volumes and dimensions, connected to the expander by varying lengths of tubes. The regenerator comprises stacked mesh sheets, and the cold head is constructed from copper. Performance metrics, including the magnetic field around the cryocooler, are both measured and calculated. The equivalent P-V work is also computed to identify key parameters and assess cooling performance. Furthermore, the study evaluates the impact of cryocooler magnetic noise on SQUID measurement systems; underscoring the importance of understanding and mitigating such noise. The development of a numerical analysis model contributes to a detailed understanding of the processes within the pulse tube cryocooler, facilitating a comprehensive design approach. The model divides the cryocooler into subsections, with each subsection further segmented into control volumes for the exchange of work, heat, and mass with its surroundings. In summary, the study provides original insights into the design, development, and performance evaluation of a Stirling pulse tube cryocooler, showcasing potential advancements in cryocooling technology.

Yibing Zhang et al. [12] The article titled "Advancements in High-Efficiency Commercial Pulse Tube Cooler" explores notable innovations in pulse tube cooling technology, with a specific focus on enhancing efficiency, reliability, and cost-effectiveness for commercial applications. A significant

enhancement involves replacing conventional flow straightener screens in the cold finger with a tapered throat, increasing resistance to working gas contamination and streamlining manufacturing processes. The article introduces the hybrid cryocooler TC4189, an upgraded version of TC4187, which integrates several innovations addressing efficiency, reliability, cost, and runtime control strategy. The use of ambient displacers to replace the inertance tube and reservoir is emphasized for its positive impact on efficiency improvement. Additionally, the article discusses the implementation of a dual-channel dual-driving mode controller as a strategy to minimize cryocooler vibration. In conclusion, the article delivers valuable insights into recent advancements in pulse tube cooling technology, providing a comprehensive overview of the innovations and their implications for efficiency, reliability, and cost-effectiveness in commercial applications.

Daming Sun et al. [13] The manuscript delves into the application of a high-capacity Stirling cryocooler to expedite the cooling process of superconducting magnets. The study introduces an innovative method to enhance the cooling efficiency of superconducting magnets by utilizing a Stirling cryocooler. However, when accounting for heat transfer temperature differences and heat leakage, the Stirling cryocooler extends the cooling time to 23 days for achieving the same temperature reduction from 300 K to 40 K. The study underscores the advantages of this approach, emphasizing system simplification and a cleaner cooling process. The findings suggest that the large cooling capacity Stirling cryocooler holds significant potential to enhance the efficiency of cooling superconducting magnets. The conclusions of the study highlight the practical implications of this technology, particularly its potential to streamline the cooling process and enhance the overall performance of superconducting magnet systems. Additionally, the manuscript provides insights into future research directions, emphasizing the need for further optimization of the cooling process and exploration of potential applications in various superconducting magnet systems. In summary, the study provides valuable insights into the potential of Stirling cryocoolers to advance the field of superconducting magnet technology, establishing a foundation for ongoing research and development in this domain.

S. C. Chikurde et al. [14] The article titled "Design and Development of A Pulse Tube Cryocooler" addresses the imperative need for a compact and maintenance-free cryocooler for Mars missions, presenting a comprehensive parametric analysis of the linear motor compressor. The primary goal of the study is to enhance the overall efficiency and operational lifespan of the cryocooler. Rigorous design and optimization are applied to key components, including the linear motor compressor, pulse tube, and regenerator unit. The parametric analysis of the linear motor compressor successfully yielded a 4% increase in efficiency for the existing design. Building upon this positive outcome, a new linear motor compressor was produced for pulse tube cryocoolers of varying capacities, showcasing an improved operational efficiency. Additionally, through the strategic manipulation of various parameters in the pulse tube and regenerator, a complementary cold head was developed, further contributing to the enhanced performance of the cryocooler. The research findings carry significant implications for space exploration missions, particularly those destined for Mars, where the demand for compact and maintenance-free cryocoolers is critical. Furthermore, the heightened efficiency and reliability of the developed cryocooler components extend their applicability beyond space exploration, benefiting industrial cryogenic systems. In summary, the study's emphasis on optimizing the linear motor compressor and associated components aligns with the urgent requirement for advanced cryocooling technologies in both space missions and industrial settings, presenting a pathway for the development of more efficient and reliable cryogenic systems.

H.J.M. ter Brake et al. [15] The Low-power Cryocooler Survey offers a comprehensive overview of current cryocooler technology, focusing on key aspects such as cooling performance, size, cost, lifetime, and reliability. One of the central themes of the survey is the significance of reliability analysis in understanding cryocooler performance. It delves into the use of reliability functions to assess the probability that a device will fulfill its intended function within a specified time period and introduces the concept of the failure rate, denoted as $k(t)$, representing the number of failures per unit of time

normalized to the number of devices still in operation at time t . The survey highlights the challenges associated with estimating reliability, particularly with respect to different time periods. It underscores that reliability estimates may be specific to the test duration or a time period shorter than the test duration. The concept of mean-time-to-failure (MTTF) is introduced as a crucial metric for evaluating reliability, emphasizing its direct correlation to the cumulative number of operating hours divided by the number of failures during operation. Furthermore, the survey provides statistical data on maintenance intervals and specified lifetimes for various cryocooler types, offering insights into the distribution of these metrics across different cooler types. It also discusses the challenges of estimating reliability beyond a certain time period, especially in the wear-out regime where the failure rate experiences a rapid increase with time. In summary, the survey delivers valuable insights into the reliability and performance of cryocoolers, positioning itself as a valuable resource for researchers, engineers, and stakeholders in the field of cryogenics and low-temperature electronics.

J. Raab and E. Tward, [16] The work delves into the realm of Small Space Cryocoolers, placing a spotlight on their advancements and indispensable capabilities for space applications. Notably, it underscores the exemplary track record of NGAS (Northrop Grumman Aerospace Systems) cryocoolers in orbit, emphasizing their proven reliability and stellar performance. The narrative extends to the evolution of cryocooler drive electronics, showcasing a collaborative effort with Oxford University to pioneer a novel, low-mass, high-performance compressor technology. This groundbreaking design has undergone substantial scaling, illustrating significant strides in cryocooler technology. Technical intricacies of these cryocoolers are thoroughly explored, offering insights into cooling loads at different stages, input power, and rejection values. Visual representations in the form of figures elucidate the configurations of high capacity and low-temperature coolers. Additionally, the document delves into vibration control strategies, highlighting the successful implementation of feedback on the drive axis to minimize vibration output. In essence, the paper stands as a testament to the remarkable advancements in small space cryocooler technology, showcasing NGAS's pivotal contributions and the triumphant deployment of these cryocoolers in space. The document aptly emphasizes the critical role played by cryocoolers in facilitating scientific research and space exploration, particularly within the domain of space infrared payloads.

Rajesh V RA and Biju T Kuzhiveli [17] The research article presents a thorough examination of the parametric study and electromagnetic analysis pertaining to a linear motor designed for a Stirling Cryocooler. Emphasizing the Stirling cycle's efficiency and environmental friendliness with helium as the working medium, the cryocooler is acknowledged for its compact size, lightweight nature, high efficiency, low power consumption, and exceptional reliability. These attributes render it suitable for applications in military and space contexts. The focal point of the analysis is the compressor component of the cryocooler, particularly the power piston responsible for compressing the working fluid. In lieu of conventional rotary motors, the article underscores the use of linear motors to drive the piston's movement. Linear motors, known for generating force in the direction of the piston's travel and offering advantages such as high speeds, rapid acceleration, and precise positioning, are discussed in detail. The article meticulously explores the impact of various geometric and electromagnetic parameters on motor performance, elucidating the significance of each parameter in the holistic design and functionality of the system. The electromagnetic analysis, grounded in the principles of electromagnetism and employing equivalent magnetic circuit analysis, is employed to determine the force generated by the interaction of magnetic fields between the coil and permanent magnet. In conclusion, the article underscores the operational flexibility of the linear motor and explores the potential applications of Stirling cryocoolers featuring linear motors in spacecraft. The prospect of replacing stored cryogens with closed-cycle coolers in spacecraft, particularly if a reliable, long-life system capable of producing milliwatts of cooling at cryogenic temperatures can be developed, is considered. Overall, the research article provides original insights into the operation and analysis of Stirling cryocoolers, presenting a compact and environmentally friendly cooling system with low energy consumption.

Virendra Bhojwani et al. [18] this research paper details the development and testing of a two-stage

Stirling Cryocooler designed for cooling IR sensors in space applications. The paper comprehensively discusses the hardware development, optimization of input and output parameters, and the experimental results of the cryocooler. The optimized parameters guided the construction of the cryocooler unit for testing, with particular emphasis on preserving the mechanical phase shift between the piston and displacer motion. Several design considerations were implemented, such as coating the piston with Rulon for sealing and oil-less operation, utilizing flexure bearings to maintain clearance, and fitting the compressor cylinder with a cast iron liner to prevent wear. Additionally, maintaining a 15 mm radial clearance between the piston and cylinder walls was crucial to prevent working fluid leakage. The cryocooler successfully met the specified objectives, achieving 2 W at 120 K at stage 1 and 0.5 W at 60 K at stage 2 during experimental tests. Overall, the paper provides valuable insights into the design, development, and testing of the two-stage Stirling Cryocooler, presenting a promising solution for cooling IR sensors in space applications. The identified gap in the literature regarding the development of miniature moving magnet pulse tube cryocoolers emphasizes the potential for further research in this domain.

STATEMENT OF PROBLEM

We have developing a miniature moving magnet pulse tube cryocooler to address the limitations in existing cryocooler technologies, especially in terms of compactness, lightweight design, durability, and maintenance-free operation, aligns with the demands of modern applications, particularly in space and similar environments. Integrating a miniature compressor and motor is essential for the functionality of the cryocooler. The design should prioritize efficiency and reliability while addressing challenges related to vibrations and maintenance commonly associated with traditional cryocooler systems. The use of a pulse tube and regenerator in your proposed design is promising, as these elements can enhance the cooling and overall performance of the cryocooler. Furthermore, the inclusion of magnetic components can reduce the number of moving parts, thereby decreasing vibrations, maintenance needs, and system complexity, ultimately enhancing the reliability and operational lifespan of the cryocooler. [26] Considering the selection of suitable materials, such as for the regenerator and pulse tube, and optimizing the thermodynamic processes to efficiently achieve the desired low temperatures will be crucial as you progress with your development. Your proposed approach to design and develop a miniature moving magnet pulse tube cryocooler aligns with the industry's push for compact, efficient, and reliable cooling solutions. It has the potential to open up new opportunities in various applications, including space.

METHOD OF RESEARCH

Aims to focus on the development, performance analysis, and testing of a miniature Pulse Tube Cryocooler with a moving magnet compressor, with the intention of increasing cooling capacity while minimizing costs and power input. Additionally, you plan to conduct a comparative study of various types of cryocoolers by developing, analysing, and testing your proposed work. This research holds significant promise in advancing cryocooler technology and could potentially lead to valuable insights into optimizing cryocooler efficiency and performance.[27] The innovative approach of integrating a moving magnet compressor with a pulse tube cryocooler presents an opportunity to enhance cooling capacity, improve energy efficiency, and keep production costs low. The comparative study you plan to undertake will provide valuable insights into how your proposed cryocooler design fares against other existing technologies, offering a comprehensive understanding of its performance and cost-effectiveness in relation to conventional cryocooler types.[28]

RESEARCH DESIGN

Initial parameter of design and development of miniature moving pulse tube cryocooler obtaining will be carried out in following stages.

1. Logical Design i.e. to identify problem, generate the specification, develop concept.
2. Modeling by using appropriate tool.
3. Development of set up by manufacturing miniature moving magnet compressor and pulse tube

- cryocooler set up with flexure bearing [29].
4. Experimentation: testing, performance analysis will be carried out.
 5. Result analysis and conclusion.

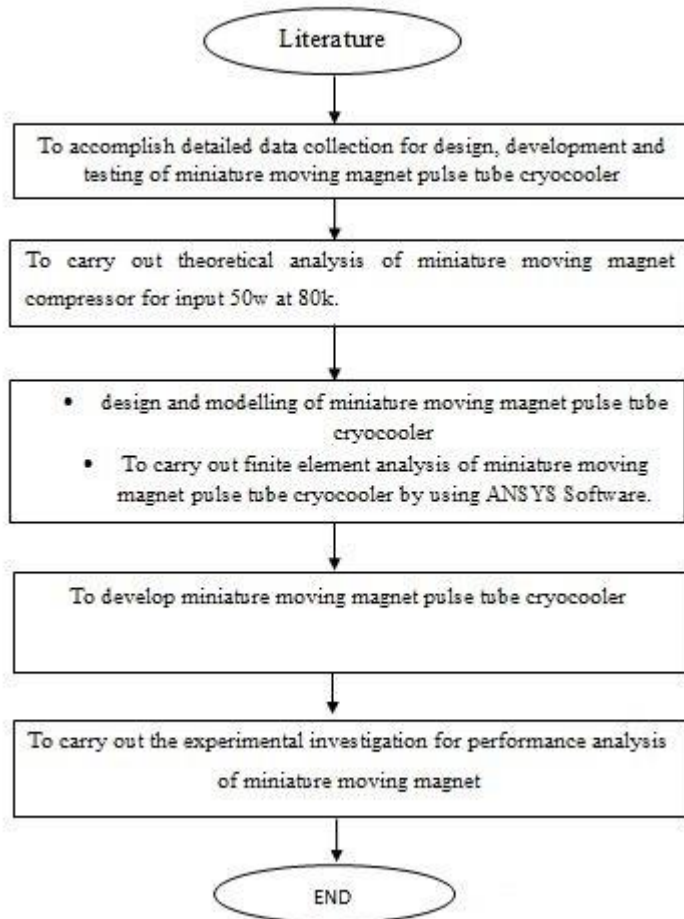


Figure 1. Methodology Flow chart [27]

CONCEPTUAL FRAMEWORK

The figure presents a conceptual framework for a miniature moving magnet pulse tube cryocooler. It outlines the key components and their interactions, illustrating the core principles behind the design and its operation within a compact and efficient system.

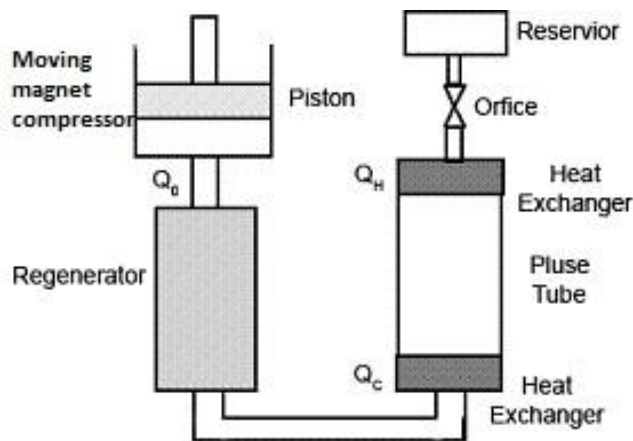


Figure 2. Moving magnet pulse tube cryocooler[30]

CONCLUSION

Cryocooler play a crucial role in enabling and maintaining ultra-low temperatures across a diverse array of applications, ranging from scientific research and medical diagnostics to industrial processes and space exploration. As cryocooler technologies continue to advance, there are anticipations of further enhancements and broader implementation in the future. While J-T cryocoolers demonstrate high efficiency in numerous applications, it is imperative to acknowledge their limitations, including cooling capacity, efficiency, power consumption, temperature range constraints, maintenance requirements, and reliability. To address these limitations, developments in Brayton Cryocoolers, Stirling Cryocoolers, and Gifford-Mahon Cryocoolers have significantly improved cooling capabilities, overall performance, and long-term stability and reliability. These advancements represent notable progress in mitigating the challenges associated with traditional J-T cryocoolers and present opportunities for enhanced and expanded utility. The ongoing evolution of cryocooler technologies, exemplified by the introduction of alternative cryocooler types, holds significant promise for overcoming the constraints of existing systems, ultimately fostering innovation and advancement across diverse industries and scientific disciplines.

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