

A Review Paper on Pulse Tube Refrigerator

Shubham Shinde¹, Sandeep Shinde², Sarvesh Sawantbirje³, Rohan Waykar⁴

^{1,2,3,4}First Bachelor of Engineering, Department of Mechanical Engineering, MGM college of Engineering and Technology.

shindess169@gmail.com ¹, samshinde79.ss@gmail.com ², triplesb2012@gmail.com ³, rohanwaykar.8@gmail.com ⁴.

Abstract - The pulse tube refrigerator (PTR) is a cryocooler which is capable of reaching temperature of a few tens of Kelvin in a single stage and a few Kelvin in two stages. Unlike ordinary refrigeration cycles which utilize the vapour compression cycle, a PTR implements the oscillatory compression and expansion of gas within a closed volume to achieve the desired refrigeration. Pulse tube refrigerator has the advantages of long-life operation, high reliability and low vibration over the conventional cryocoolers, such as G-M and Stirling coolers because of the absence of moving parts at their low temperature end. Due to its associated advantages, pulse tube refrigerators have several applications such as cooling of infrared sensors, night vision equipments, SQUID, cryopumping, etc. Our objective was to change the material of the Pulse tube and increase the efficiency of the system. Steel was the base material selected and Copper and Aluminium was selected for the study. Finite element software ANSYS workbench 18.0 is used to perform the CFD analysis under a standard working condition to find performance parameters.

Key Words: Pulse Tube Refrigerator, Vapour compression cycle, Cryocoolers, CFD Analysis.

1.INTRODUCTION

Cryogenics comes from the Greek word “kryos”, which means very cold or freezing and “genes” means to produce. Cryogenics is the science and technology associated with the phenomena that occur at very low temperature, close to the lowest theoretically attainable temperature. In engineering, cryogenics can be best described as an application which operates in the temperature range from absolute zero to about 123K(-150°C). In particular, this includes refrigeration, liquefaction, storage and transport of cryogenic fluids, cryostat design and the study of phenomena that occur at these temperatures.

Cryocooler is a refrigeration machine with refrigeration temperature below 123K and with a small refrigeration capacity. According to the classification by Walker (1983) there are two types of cryocoolers: recuperative type and regenerative type. The former includes the Joules Thomson cryocooler and the Brayton cryocooler. The latter includes the Stirling type cryocooler and the Gifford-McMahon type cryocooler. These cryocoolers as enumerated by Radebaugh

(1995), are mainly used for cooling of the infrareds sensors in the missile guided system and satellite-based surveillance, as well as in the cooling of superconductors and semiconductors. The cryocoolers can also be used in other applications such as in cryopumps, liquefying natural gases, cooling of radiation shields, SQUID (super conducting quantum interference device), Magnetometers, SC Magnets, Semiconductor fabrication etc.

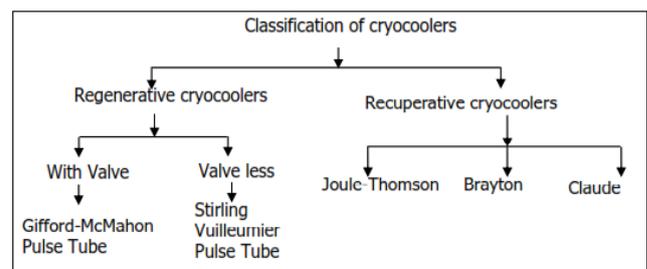


Chart -1: Classification of Cryocoolers

1.1 Application of Cryocoolers

Before The major applications of cryocoolers are summarized below:

- I. Military
 - a) Infrared sensors for missile guidance & night vision.
 - b) Infrared sensors for surveillance (satellite based).
 - c) Gamma-ray sensors for monitoring nuclear activity.
 - d) Superconducting magnets for mine sweeping.
- II. Environmental
 - a) Infrared sensors for atmospheric studies (satellite).
 - b) Infrared sensors for pollution monitoring.
- III. Commercial
 - a) Cryopumps for semiconductor fabrication.
 - b) Superconductors for cellular phone base stations.
 - c) Superconductors for voltage standards.
 - d) Superconductors for high-speed communications.
 - e) Semiconductors for high-speed computers.
 - f) Infrared sensors for NDE and process monitoring.
 - g) Industrial gas liquefaction.
- IV. Medical
 - a) Cooling superconducting magnets for MRI.

- b) SQUID magnetometers for heart and brain studies.
- c) Liquefaction of oxygen for hospital and home use.
- d) Cryogenic catheters and cryosurgery.

1.2 Working Principle of Pulse Tube Refrigerator

The pulse tube refrigerators (PTR) are capable of cooling to temperature below 123K. Unlike the ordinary refrigeration cycles that utilize the vapour compression cycle as described in classical thermodynamics, a PTR implements the theory of oscillatory compression and expansion of the gas within a closed volume to achieve desired refrigeration. Being oscillatory, a PTR is a non-steady system that requires time dependent solution. However, like many other periodic systems, PTRs attain quasi-steady periodic state (steady-periodic mode). In a periodic steady state system, property of the system at any point in a cycle will reach the same state in the next cycle and so on. A Pulse tube refrigerator is a closed system that uses an oscillating pressure (usually produced by an oscillating piston) at one end to generate an oscillating gas flow in the rest of the system. The gas flow can carry heat away from a low temperature point (cold heat exchanger) to the hot end heat exchanger if the power factor for the phasor quantities is favourable. The amount of heat they can remove is limited by their size and power used to drive them.

1.3 Components of Pulse Tube Refrigerator

I. Compressor

The main function of the compressor is to supply gas pressurization and depressurization in the closed chamber. Electrical power is applied to the compressor where this electrical work is converted into the mechanical energy associated with sinusoidal pressure waves, resulting in gas motion. In an ideal compressor, the electrical power provided to the compressor must be equal to $\int P dV$, where the integration is performed over an entire cycle, P is the compressor pressure, and f is the compressor frequency. In an actual system, however, the above-mentioned power (the PdV power) is always less than the actual measured electrical power due to the associated irreversibility. Usually reciprocating nature of compressor is used in case of Stirling model; it may also be a dual opposed piston type.

II. After cooler

The function of the ideal after cooler is to extract all the heat that is generated in the compressor volume during the gas compression and dispose to environment. This minimizes the warm end temperature so that the regenerator can work more efficiently and supply low temperature working fluid to the system. Typically, these types of heat exchangers are assembled using copper wire mesh screens that are directly in contact with the housing wall.

III. Regenerator

The regenerator is the most important component in pulse tube refrigerator. Its function is to absorb the heat from the incoming gas during the forward stroke and deliver that heat back to the gas during the return stroke. Ideally, PTC regenerators with no pressure drop and a heat exchanger effectiveness of 100% are desired, in order to achieve the maximum enthalpy flow in the pulse tube. The performances of the real regenerators are of course far from ideal. Stainless steel wire screens are usually selected as the regenerator packing material, since they offer higher heat transfer areas, low pressure drop, high heat capacity, and low thermal conductivity. A typical regenerator housing is shown in Fig.1.



Fig.1: Typical pictures of Regenerator and Pulse tube

IV. Cold Heat Exchanger (CHX)

CHX can be best viewed as the equivalent of the evaporator in the vapor compression refrigeration cycle. This is where the refrigeration load is absorbed by the system. This is the junction of the regenerator and pulse tube. Copper wire mesh screens are used to exchange heat with the housing wall, and thereby receive the applied heat load.

V. Pulse Tube

The pulse tube is the most critical component of the whole refrigerating system. The main objective of the pulse tube is to carry the heat from the cold end to the warm end by an enthalpy flow. By imposing a correct phase difference between pressure and mass flow in the pulse tube by phase shifting mechanisms, heat load is carried away from the CHX to the WHX. Physically, the pulse tube is simply a hollow cylindrical tube made up of stainless steel with an optimum thickness to enhance the surface heat pumping. A typical picture of pulse tube is shown Fig.1.6 (b).

VI. Hot Heat Exchanger (HHX)

Hot end exchanger is where the gas rejects heat of compression in every periodic cycle of operation. Upon receiving the enthalpy flow from the pulse tube, the heat load at a higher temperature is rejected to the environment. Usually, air cooling or water cooling system is used to take away the heat from the hot end exchanger.

VII. Orifice Valve, Inertance Tube and Surge Volume

The role of either the Inertance tube or the orifice valve is to appropriately adjust the phase difference between the mass flow rate and the pressure. By controlling the orifice

diameter or the Inertance tube diameter and length, the desired phase relationship can be obtained. In general, the orifice valve is a needle valve, and the Inertance tube is an open cylindrical stainless tube. In comparison with the aforementioned pulse tube, the Inertance tube is much longer, and its diameter is much smaller. The surge volume can be viewed as a closed buffer reservoir of sufficient volume to allow for small pressure variations resulting from the oscillating mass flow.

VIII. Rotary valve

The rotary valve is one of the critical components of a GM type pulse tube refrigerator. The schematic diagram of rotary valve is shown in Fig.2 It is used to switch high and low pressure from a helium compressor to the pulse tube system. The high and low pressure of helium compressor are connected to the rotary valve through the quick disconnect couplings. The rotary valve has a rulon part which is made to rotate with the help of a synchronous motor against an aluminium block with predefined passages connecting the high and low pressures from the helium compressor. The rotational frequency of the synchronous motor is controlled using an inverter drive. The rotary valve has been designed to produce pressure wave in the frequency range from 1Hz to 3Hz.

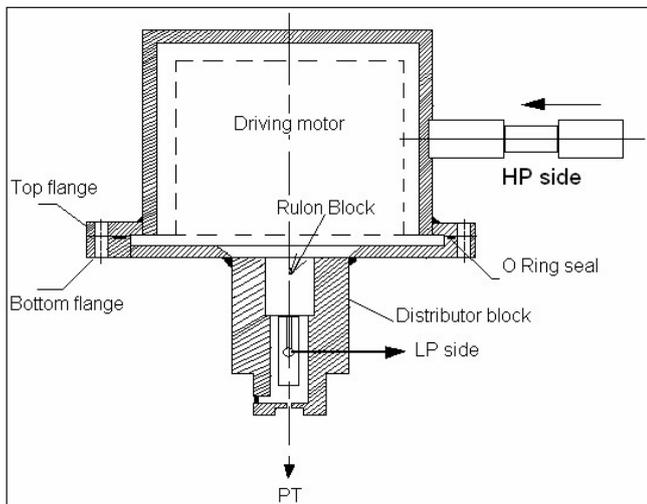


Fig. 2: Schematic Diagram of Rotary Valve

2. LITERATURE REVIEW

^[1]Banjar et al. have analyzed CFD simulations for OPTR and ITPTR. They have taken different frequency, and have used dual opposed piston compressor. They stated that at higher frequency turbulence and recirculation of fluid can be observed, which harms the overall performance of the system. From CFD simulation results they reach to the conclusion that for an optimum frequency for each PTR model, it can deliver maximum refrigeration.

^[2]Gifford and Longworth (1964) of Syracuse University introduced pulse tube refrigerator in 1963. The innovation of pulse tube models for research purpose actually started in 1963, but in 1964 the first paper was published. In that paper the concept of “the depressurization and pressurization of any kind closed volume from a point on its periphery sets up temperature gradients in the volume” was discussed. The first design was made up of a hollow cylindrical tube. It has one end open but the other end is kept closed. The closed end is kept in contact with a heat exchanger of ambient temperature, while the other end which was open was connected with cold end. Because of the oscillatory flow done by piston, the open end was forced to an oscillatory pressure from the regenerator, resulting the open end to chill. In their second paper, Gifford and Longworth showed useful cooling in a pulse tube working below critical pressure ratio.

^[3]B.J.Huang et. al. (2001) they have concluded experimentally that there exists an optimum operating frequency which increases with decreasing pulse tube volume. For a fixed pulse tube volume, increasing the pulse tube diameter will improve the performance. The experimental results are used to derive a correlation for the performance of OPTR which correlates the net cooling capacity with the operating conditions and the dimensions of the OPTR.

^[4]Richardson et al. (1989) stated that valve pulse tube OPTR have potential to reach much less temperatures. The pulse tube refrigerator may offer an alternative to cryocooler designs such as those based on the Stirling cycle or of the Gifford-McMahon type. In the pulse tube, refrigeration is produced without the use of active components operating at low temperature thus obviating a major source of unreliability. Despite this potentially significant advantage pulse tube refrigeration apparently has never been exploited in a practical cryocooler design. Although the coefficient of performance of a pulse tube refrigerator is likely to be lower than that of alternative systems it is not apparent why this should be sufficient to account for the relative lack of interest in the device given its obvious advantage of inherent reliability. This Paper reviews previous pulse tube research and presents both theoretical and experimental results from a new investigation which help explain the nature of the device. The analysis includes a method of predicting optimum pulse rate. It is possible that a better understanding of pulse tube refrigeration may provide an insight into the non-ideal behaviour observed in other types of cryocooler.

^[5]Ray Radebaugh (1987) introduced a variation of the Stirling cryocooler, known as a pulse tube refrigerator, requires only one moving part - a pressure wave generator at room temperature. The Stirling cryocooler requires in addition a moving displacer at low temperatures to cause a phase shift between pressure and mass flow rate that leads to a refrigeration effect. This paper generalizes the Stirling cycle and shows how instantaneous heat transfer or flow through an orifice can cause a similar phase shift without a

moving displacer. Temperatures as low as 60 K have been achieved in a one-stage device where an orifice is used for the phase shifting.

3. METHODOLOGY

- I. Studying the existing pulse tube refrigerator working characteristics, effectiveness, efficiency, losses:

Out of the various methods available in refrigeration, Pulse tube has upper hand due following advantages. There is no moving part in pulse tube system. Very low temperatures can be achieved. Hence we have chosen pulse tube refrigerator as research domain. For the analysis of PTR we have studied various types of existing PTR along with its involvement in different areas, its working characteristics, its effectiveness in various applications.

- II. Material selection:

For cryogenics applications, materials must be carefully selected because of the drastic changes in the properties of materials when they are exposed to extreme low temperatures. Materials which are normally ductile at atmospheric temperatures may become extremely brittle when subjected to temperatures in the cryogenic range, while other materials may improve their properties of ductility. Once the materials are selected, the method of joining them must receive careful consideration to insure that the desired performance is preserved by using the proper soldering, brazing, or welding techniques and materials. When properties of materials which are being considered for cryogenic uses are unknown, or not to be found in the known guides, experimental evaluation should be performed before the materials are used in the system. The mechanical properties of materials are considerable importance in the design of cryogenic systems. The two properties that are most often of concern are the level of stress within the material and the modulus of elasticity, E. Based on their properties determined at low temperature, only some suitable materials are used in cryogenics field. Some materials which are suitable for cryogenic temperatures are stainless steel, copper, brass, monel, titanium and aluminium and its alloys.

Selection of Aluminium over Stainless steel:

- Low weight for same amount of thermal conductivity.
- Low cost as compared to steel
- Easy in shaping compared to steel
- Lower maintenance.

Selection of Copper over Stainless steel:

- Thermal conductivity
- Heat capacity
- Thermal diffusivity
- Heat transfer rate

- III. Obtaining its CFD model and simulating its working condition:

We have made the 2D axis-symmetric model of orifice pulse tube refrigerator. We have used the design modeller of ANSYS 18.0. The dimension of orifice pulse tube was obtained from literature reviews [1].

- Select XY plane and create sketch 1 using sketch tool.
- Go to sketching mode. Draw the compressor geometry as given in specification.
- Once the sketch is made. Select create surface from sketches from concept menu.
- Likewise create all the components of orifice pulse tube refrigerator in systematic manner.
- Once all the surfaces are being made, convert them to fluid medium from part and body menu in outline tree.
- Now combine the connected component using joint tool from tool menu.

- IV. Implementing methods that are ought to improve the performance of existing pulse tube refrigerator:

There are various methods that can be applied to improve the performance of existing PTR. By changing the material of the existing PTR with material either having better thermal conductivity or cost effectiveness or both. Keeping these criteria in mind we have shortlisted copper and aluminium as alternative for the current working material i.e. stainless steel.

- V. Performing CFD analysis and comparing the results with original model:

CFD simulation using ANSYS Fluent 18.0 was performed using the boundary conditions. The obtained results were compared with the original model.

4. CONCLUSION

- Copper pulse tube in pulse tube refrigeration system is more effective than steel pulse tube.
- Copper pulse tube is 11.12% more efficient than steel pulse tube.
- Replacement of steel pulse tube with copper pulse tube is advisable.
- Aluminium pulse tube is less effective than steel pulse tube, thus replacement with it, is not advisable.
- Rate of heat removal from fluid is more in copper pulse tube than that in steel pulse tube.

5. FUTURE SCOPE

Like Trapezoidal Pressure curve different pressure profile can be generated using UDF like triangular rectangular. In this thesis only for Orifice Pulse Tube Refrigerator the analysis has been done. For different type of Pulse Tube like

Inertance tube Pulse tube, Double inlet pulse tube taking trapezoidal pressure profile analysis can be done for different boundary condition like adiabatic condition to get minimum temperature for no load, Isothermal condition to get refrigeration effect for a specific temperature, analysis for a known load condition to get minimum temperature for a given refrigeration effect.

REFERENCES

- [1] Y.P. Banjar, Theoretical and Experimental Studies on Pulse Tube Refrigerator, PhD Thesis (2009), National Institute of Technology Rourkela, India.
- [2] Gifford, W.E. and Longsworth, R.C. Pulse tube refrigeration, Trans ASME B J Eng. Industry 86(1964), pp.264-267.
- [3] B.J. Huang and G.J. Yu, Experimental study on the design of orifice pulse tube refrigerator, International journal of refrigeration (2001)
- [4] Richardson, R. N., Valved pulse tube refrigerator development, Cryogenics30 (1989), pp. 850853
- [5] Ray Radebaugh, The Japanese journal of Physics, (1987), Volume 26, Supplement 26-3, Part 3.