Experimental Analysis and Development of A Single Stage High Refrigerating Capacity of Pulse Tube Refrigerator

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Abstract:* The absence of moving components at low temperature end gives the pulse tube refrigerator (PTR) a great leverage over other cry coolers like Sterling and G-M refrigerators that are conventionally in use for several decades. PTR has greater reliability; no electric motors to cause electromagnetic interference, no sources of mechanical vibration in the cold head and no clearance seal between piston and cylinder. Moreover, it is a relatively low cost device with a simple yet compact design. The objectives of the present work is to design, fabricate and test a single stage G-M type pulse tube refrigerator and study its performances. Experimental studies consists of cooling behavior of the refrigeration system at different cold end temperatures and optimization of orifice and double inlet openings at different pressures. The developed pulse tube refrigerator consists of compressor, rotary valve, regenerator, pulse tube, hot end heat exchanger, orifice valve and double inlet valve, reservoir or buffer, vacuum chamber and coupling accessories etc. Regenerator and pulse tube have been chosen according to the literature available. Hot end heat exchanger has been designed and fabricated with respect to the regenerator and pulse tube geometry. The assembly of the components has been done in such a way that the set-up can be used as basic pulse tube refrigerator, orifice pulse tube refrigerator or double inlet pulse tube refrigerator as and when required. This has enabled thorough comparison among them. The effect of operating conditions such as average pressure and pressure ratio of the compressor also has been found out. The optimum operating conditions such as opening of the orifice and double inlet valves have been selected according to the performance i.e. minimum attainable temperature at no load condition. Effect of orifice and double inlet openings at different pressures has been detected by applying the pressure sensors across at various positions in the system. Correspondingly, pressure variations at regenerator inlet, pulse tube and reservoir have been determined.

***Keywords:* pulse tube refrigerator, double inlet, design, fabrication, testing, optimization, cooling behavior, pressure variation.**

I. INTRODUCTION

Cryogenics literally means ‘icy cold’ and is referred to the technology and science of producing low temperatures. However, the term cryogenics generally refers to the entire phenomena occurring at temperatures below 123 K, and processes, techniques and apparatus needed to create or maintain such low temperatures. An increased need for cryogenic temperatures in many areas of science and technology in the last few decades caused a rapid development of cryocoolers. Cryocoolers are refrigerating machines, which are capable of achieving cryogenic temperatures.

Cryocoolers are used in various applications due to high efficiency, high reliability, low cost, low maintenance, low noise level etc. However the presence of moving parts in the cold zone of the most of the cryocoolers makes it difficult to meet all these requirements. A new concept in cryocoolers, pulse tube refrigerator (PTR) has overcome some of these drawbacks. A PTR is a closed cycle mechanical cooler without any moving components, working in the low temperature zone. Conventionally, there exists two types of cooling technologies: open cycle and closed cycle. The open cycle cooling technique, which included the evaporation of stored cryogen and joule-Thomson expansion of pressurized gas, may be relatively low cost and good reliability. But their application is quite limited since they often present logistic problems.

The closed cooling system which includes G-M, Stirling and Joule-Thomson cycles are more favourable. The main distinction of cryocoolers from other closed cycle mechanical coolers is that the PTR has no moving parts in the low temperature region and therefore, has a long life and low mechanical and magnetic interferences.

The operating principle of the PTR is based on the displacement and the expansion of gas in the pulse tube that results in the reduction of the temperature. Usually helium is used as the working fluid in all closed cycle cryocoolers, including PTR. The working fluid undergoes an oscillating flow due to an oscillating pressure. A typical average pressure in a PTR is 10 to 25 bar. A piston compressor (in case of a Stirling type PTR) or a combination of a compressor and a set of switching valves (G-M type PTR) is used to create pressure oscillation in a PTR. The regenerator of the PTR stores the heat of the gas in its matrix during a half cycle and therefore must have a high heat capacity compared to the heat capacity of the gas.

The concept of pulse tube refrigeration was first introduced by Gifford while working on the compressor in the late 1950's,he noticed that a tube, which branched from high-pressure line and closed by a valve was hotter at the valve than at the branch. He recognized that there was a heat pumping mechanism that resulted from pressure pulses in the line. Thus, in 1963 Gifford together with Longsworth introduced the Pulse tube refrigerator, which is termed as the Basic Pulse Tube (BPT) refrigerator.

1. Pulse tube
2. Orifice
3. Reservoir
4. Double inlet valve
5. Cold end heat exchanger
6. Regenerator
7. Compressor

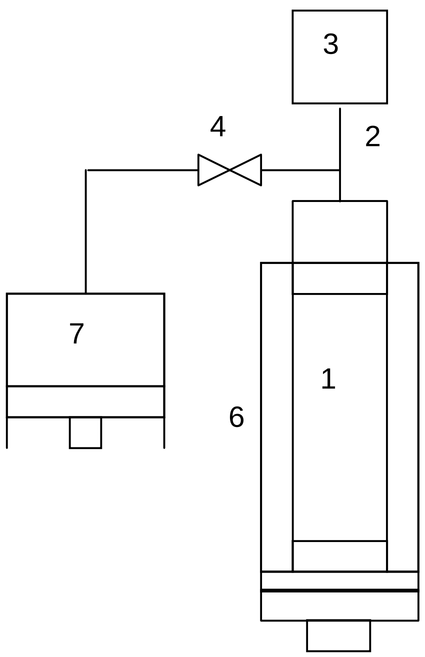

Figure 1: Schematic of Co- axial Pulse tube refrigerator

It does not carry heat in or out of the system but it absorbs heat from the gas during one part of the pressure cycle and returns this heat to the gas during the other part. The high heat capacity of the regenerator matrix with respect to that of the working fluid permits it to store the cooling effect generated in the pulse tube by alternatively cooling down and heating up the gas which flows through it.

The pulse tube is considered as the heart of a PTR system and is a thin walled stainless steel tube. The gas inside the pulse tube experiences the cooling effect, if there is a suitable phase shift between the pressure and the gas flow in the tube. The two heat exchangers located in the cold and warm ends of the pulse tube act as flow straightness. The cold end heat exchanger is the coldest point of the system. Here the PTR absorbs heat from the device to be cooled.

II. LITERATURE REVIEW

Gifford and Longsworth [2019] developed a relationship for the cold end temperature with zero heat pumping rate in terms of length ratio, hot end temperature and the ratio of specific heats of gas with the help of surface heat pumping (SHP) mechanism.

Colangelo et al [2019] developed a simplified heat transfer model for the performance analysis of basic pulse tube refrigerators. This model takes into account the heat and mass transfer processes in the regenerator and pulse tube. They assumed that the convective heat transfer between the gas and pulse tube wall or regenerator matrix during flow periods is a controlling mechanism.

Gifford and Kyanka [2018] returned to the problem of reversible pulse tube and attempted to compare with that of a valved pulse tube, although it would seem that the experimental comparison was based on limited data. The pressure ratio used in this work was 4.2:1 and a low temperature limit of 165 K was achieved. It was concluded that other factors being equal and the refrigeration capacity of a reversible pulse tube is inferior to that of the valved type.

Narayankhedhkar and Mane [2017] did theoretical and experimental investigations on pulse tube refrigerator. The method for the derivation of cold end temperature with zero heat pumping rates was introduced. Lowest cold end temperature obtained with air as the working fluid was 214.5 K, with a frequency of 50 Hz. Experimental investigations indicated that there exists an optimum speed and hot end length, and this speed decreases with increase in the total length of pulse tube. They verified Longsworth's conclusion about the variation of heat pumping rate with pulse tube length by experiments up to a total length of 550 mm and with air as the working fluid.

Mikulin et al. [2016] The main achievement when and his co-workers published their innovative modification of the basic pulse tube refrigerator. They showed that the efficiency of pulse tube refrigerator could be increased by fastening a reservoir to the warm end of the pulse tube, through an orifice instead of being closed. Using air as the working fluid, they achieved a low temperature of nearly 105 K and the net refrigeration capacity at 120 K was ~10 W.

III. PROBLEM IDENTIFICATION

The most important parameter to achieve cooling capacity and lowest temperature is by varying frequency and can be observed in Stirling and G-M type PTRs. G-M type achieves much lower temperature rather than Stirling one but less efficient.

- The behavior of the 4 K regenerator, such as an extended region of constant temperature near 4 K and comparatively large mass flow rate at the cold end are completely different from the behavior of regenerators working at higher temperatures.
- A configuration of the pulse tube cooler where the phase shifter located at room temperature is not capable for an efficient phase shifting of the moving liquid helium at the cold end.
- Double inlet operation significantly improves the performance of 4 K pulse tube coolers by reducing mass flow rate and losses in regenerator. A DC flow through the double inlet tube was discovered in the simulation.

The objectives of the research work are

- To conduct an up-to-date survey of literatures on experimental works on single stage and multi stage pulse tube refrigerators.
- To develop an indigenous G-M type single stage pulse tube refrigerator operating at a high cooling capacity of 200 W at 70 K.
- To conduct experimental studies on double inlet configuration of pulse tube refrigerator and study its performances at optimum level.

IV. METHODOLOGY

The main components of the pulse tube refrigerator such as regenerator, pulse tube, hot end heat exchanger and reservoir have been designed and fabricated. The present pulse tube cryocooler is of single stage double inlet configuration. It has been designed for a cooling capacity close to 100W to 200 W. Detailed drawings of the components are available in appendix.

Regenerator is a thermal energy storage device. The thermal energy is stored in porous matrix of high heat capacity material and used to heat and cool a fluid flowing through the matrix. The matrix cools the incoming fluid stream to working temperature and warms the exhaust stream to ambient. Another way a matrix is cooled by the exhaust stream and warmed by the incoming stream. It maintains a constant temperature gradient over the inlet and outlet at steady operating condition. The regenerator used in the experiments is stainless steel tube of external diameter Φ51 mm, 180 mm in length with 1 mm thickness is shown in Fig.3.

Regenerator materials and geometries are to be selected based on the temperature range over which they are most commonly used. The most commonly used woven wire screen used for the regenerator is stainless steel because it is easy to weave in to the screen. It is used over temperature range from 30 to 300 K, where it provide the following advantages.

- Low pressure drop
- High heat transfer area
- Low axial conduction
- High heat capacity

The woven wire of stainless steel mesh screen is most commonly used regenerator material. It is readily available in useful mesh sizes from 50 mesh to over 250 mesh. It is available in different materials and relatively inexpensive to use. The small diameter and high thermal conductivity of the wire used to weave the screen provides full utilization of the thermal capacity of the material. In the present case, stainless steel mesh screens of size 250 and copper mesh screen size of 40 have been taken.

Fig. 2 (a) Stainless steel mesh

Fig.2 (b) Copper mesh

The stainless steel wire mesh is first cut in to roughly square pieces and stacked one over another till a long stack is obtained. Then this stack is machined on a conventional lathe to get the circular stack of meshes to be fitted in to the tube. This is done to obtain a tight packing inside the regenerator tube and to minimize occurrences of air spaces, to increase its heat capacity and hence its effectiveness. For every tenth layer of stainless steel mesh, copper meshes have been inserted in order to maintain the temperature uniformity.

Optimization of the regenerator is one of the main problems associated with the development of a pulse tube refrigerator. For example, by increasing the filling factor, the pressure drop becomes higher. Another difficulty is regarding the fixation of the regenerator material inside the regenerator.

Fig.3 (a) Top flange of Regenerator

Fig.3 (b) Bottom flange of Regenerator

Fig.4 Photographic view of Regenerator

In the experimentation of pulse tube cryocooler, the regenerator material is very standard and the mesh type commonly used is stainless steel of mesh size 250. Copper is also used along with stainless steel for temperature uniformity. When it achieves low temperatures, the specific heat of stainless steel will become very small and then the preferred regenerator material are lead balls, Er_3Ni etc. However, the optimization of the regenerator material and fixation are highly complicated in the experimentation.

The pulse tube is most critical component of the whole refrigeration system. This is the component where main functioning works. But geometrically, as well as from the fabrication point of view this is the simplest component of the system. Only a thin walled stainless steel tube is used to reduce the axial heat transfer over the large temperature gradient between the cold and hot end heat exchangers. The main objective of the pulse tube is to carry the heat from the cold end to the warm end by an enthalpy flow. The pulse tube used in the present case is stainless steel tube of external diameter Φ45 mm, 250 mm in length of 1 mm thickness with end flanges.

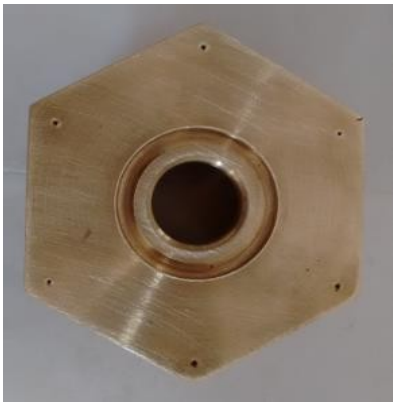

Fig.5 (a) Top flange of Pulse tube

Fig.5 (b) Bottom flange of Pulse tube

V. RESULT & DISCUSSION

Experimentation has been carried out on the pulse tube refrigerator test rig by varying the different inputs such as charging pressure, double inlet valve opening and orifice valve opening. The set-up has been operated as BPTR, OPTR and DIPTR to study its performances and effects at cold end temperature.

OPTR and DIPTR have been shown better cool down characteristics compared to BPTR. Since the compressor is of small capacity of 1.5 kW, the steady state obtained is slow. By trail run it has been found that pulse tube refrigerator comes in steady operation after 3600 seconds

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(approx.). Figures of (6 to 8) have shown the cool down behaviour when operated at basic, orifice and double inlet type respectively at their particular operating condition. It has been found that higher pressure gives the minimum cold end temperature i.e. better performance. It has been seen that higher orifice opening gives lower cooling but comes steady state quickly compared to smaller opening. The cold end temperature decreases with the increase of pressure due to higher compression and expansion of the gas inside the tube.

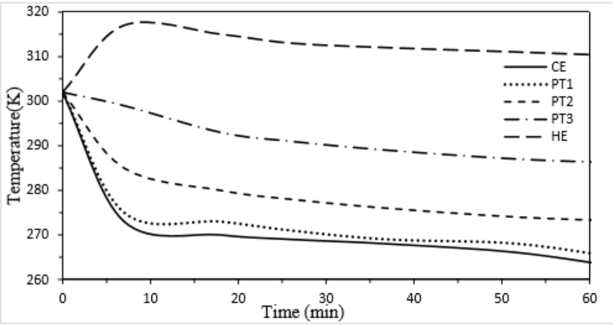

Fig. 6: Cool down behaviour at optimum opening of orifice valve at HP =10 bar and LP=8 bar at no load as OPTR.

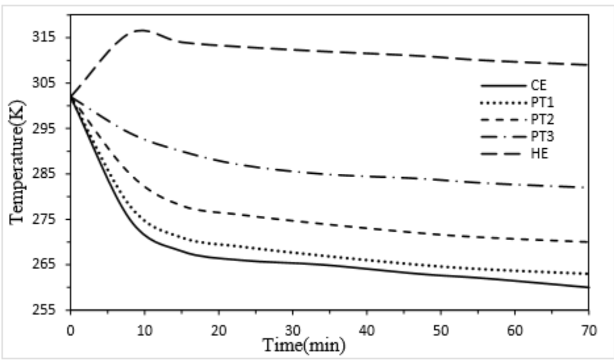

Fig. 7: Cool down behaviour at optimum opening of double inlet valve at HP 10 bar and LP=8 bar at no load as DIPTR.

A temperature of 260 K has been observed at high pressure of 10 bar and low pressure of 8 bar when operated at optimum opening of double inlet valve at 0.197 inches and of orifice at

0.152 inches. At an optimum orifice opening of 0.158 inches a temperature of 262 K at cold end has been achieved at same pressure when operated as orifice type.

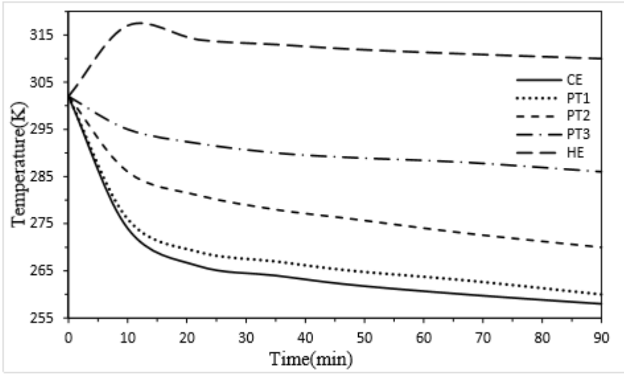

Fig. 8: Cool down behaviour at optimum opening of double inlet valve at HP =14 bar and LP=10 bar at no load as DIPTR.

VI. CONCLUSION AND FUTURE SCOPE

Experimental studies have been made on pulse tube refrigeration system. Previous chapters contain the details of the investigation. The salient results and features have been highlighted in the present chapter.

- A pulse tube refrigerator along with the test-rig has been designed and fabricated indigenously. Elaborate studies have been carried out to optimize the developed system.
- Cooling behavior of the pulse tube refrigerators has been studied at different average pressures and at different openings of the flow resistance valves. Some distinct features of OPTR and DIPTR compared to BPTR have been discussed.
- Optimum opening of the flow resistance valves (orifice and double inlet valve) has been determined according to minimum attainable cold end temperature at no load condition.
- Instead of single valve double inlet type, a double valve double inlet configuration has been developed.

Some recommendations of these includes

- In the present, studies could not be made at different frequencies of the rotary valve. However, this is a very important parameter. Extensive studies are needed to identify the optimum frequency.
- Well planned strategy of the experimental studies showed can be taken to optimize the geometry of

pulse tube.

- Scope of improvement also exists in the design of regenerator.
- Present studies are mainly focused on the effect of cold end temperature and can be extended further to study on the effect of cooling capacity.
- The developed facility set-up can be extended to study the performance of the inertance tube and minor orifice type pulse tube.
- Scope of commissioning the test set-up by a high kW compressor for high refrigerating capacity and for the study of better performances.

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