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EXPERIMENTAL STUDIES TOWARDS DEVELOPMENT OF A SINGLE STAGE HIGH REFRIGERATING CAPACITY G-M TYPE 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 cryocoolers like Stirling 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.

***Index Terms*— Pulse tube refrigerator; double inlet; design; fabrication; testing; optimization; cooling behavior; pressure variation.**

I. BACKGROUND & MOTIVATION

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.

Objectives

This study aims at broadening the level of understanding of the operations of pulse tube refrigerators. An effort has been made to achieve this by experimental investigations.

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.

II. LITERATURE REVIEW

A. Introduction

In this chapter, principle of operation and a brief classification of pulse tube refrigerators are discussed. The various developments took place in the area of PTRs, since its invention in 1964 and the sources of information are presented in a chronological manner.

B. Pulse Tube Refrigerator

Cryocoolers, finds wide variety of applications, hence it should be efficient, reliable, durable, economical and less noisy. However, the presence of moving parts in the cold area of most of the cryocoolers makes it difficult to meet all these requirements. The concept of a new cryocooler called the pulse tube refrigerator (PTR) was first introduced by Gifford [1], while working on the compressor in the late 1960’s. He noticed that a tube, which branched from high-pressure line was 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 1965 Gifford together with his assistant Longsworth introduced the concept of Pulse tube refrigerator, which is currently named as the Basic Pulse Tube (BPT) refrigerator. The cooling principle of the BPT refrigerator is the surface heat pumping, which is based on the exchange of heat between the working gas and the pulse tube walls. The lowest temperature reached by Gifford and Longsworth with the BPT refrigerator, was 124 K with a single stage. Ironically, this is not the basis of the present day pulse tube refrigerators.

Mikulin et al. [6] developed a new type of pulse tube refrigerator called, Orifice Pulse Tube (OPT) Refrigerator which has revolutionized the pulse tube technology in the year 1984. This invention resulted in a rapid achievement in the field of cryocoolers and brought an avalanche of new ideas, all with the intention to improve the performance of cryocoolers. The most important types of pulse tube refrigerators are discussed in the following section.

1) Principle of operation

The operation principles of PTRs are very similar as conventional refrigeration systems. The methods of removing heat from the cold environment to the warm environment are somewhat different. The vapour compression cycle shown in Fig.2.1 operates in a steady flow fashion where heat is transported from the evaporator to the condenser by a constant and steady mass flow rate. The PTR relies on an oscillatory pressure wave in the system for transporting heat from the cold end heat exchanger to hot end heat exchanger.

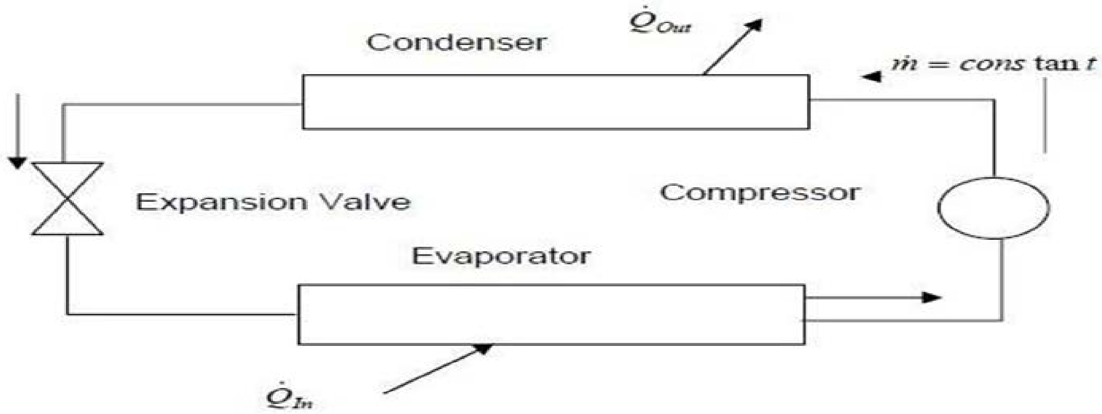


FIG.2.1 SCHEMATIC DIAGRAM OF THE SIMPLE VAPOUR COMPRESSION CYCLE

2) Advantages of PTR over G-M and Stirling Cryocoolers

- Absence of displacer at cold end.
- Simple construction and reduced cost.
- Higher reliability.
- Reduced vibrations.
- Low mechanical and magnetic interferences

3) Limitations of PTR over G-M and Stirling Cryocoolers

- Requirement of more gas to pass through pulse tube and reservoir. Hence, viscous losses are increased.
- Difference in density gives rise to convection currents; if the machine is tilted. Thus the performance of the device becomes orientation dependent.

4) Applications of Pulse Tube Refrigerator

The application area of cryocoolers is very large. Most of the applications require high efficiency and reliability of a cooler as well as its long lifetime and a low cost. Advances in the cryogenic technology and cryocooler design have opened the door for potential applications in cryogenically cooled sensors and devices such as:

- Missile tracking sensors
- Unmanned Aerial Vehicles (UAVs)
- Infrared (IR) search and track sensors
- Satellite tracking systems
- Pollution monitoring sensors
- High Resolution imaging sensors
- Magnetic Resonance Imaging (MRI) and Computer Tomography (CT) for medical diagnosis and treatment.

Studies further indicate that Cryogenic technology has potential applications to Photonic devices, Frequency (RF) sensors, Electro-Optic components and Opto-Electronic devices.

III. DESIGN AND FABRICATION OF PULSE TUBE REFRIGERATOR

A. Introduction

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.

B. Regenerator

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.3.3.

1) Regenerator Materials

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

2) Wire mesh screen

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.

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.

C. Pulse tube

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.

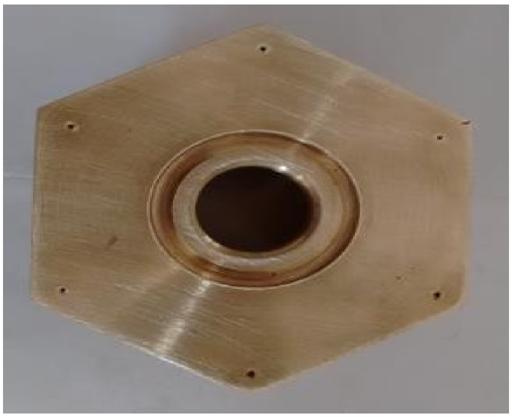
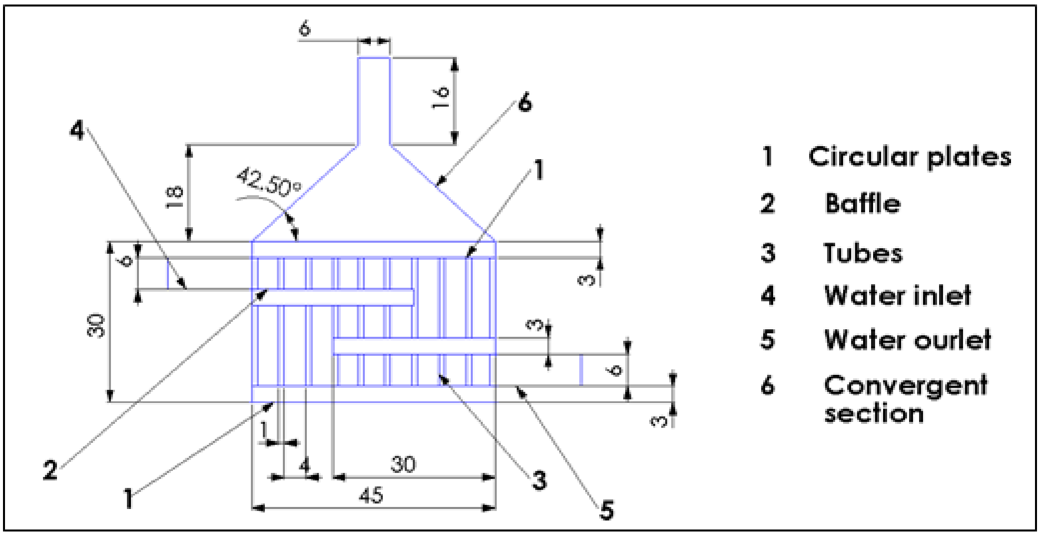


Fig.3.4 (a) Top flange of Pulse tube

Fig.3.4 (b) Bottom flange of Pulse tube

D. Hot end heat exchanger

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. A shell and tube type heat exchanger has been designed and fabricated to extract heat out of helium gas at the hot end of pulse tube [39]. Helium gas flow through a total of 55, 4 mm outer diameter with 0.5 mm thickness capillary copper tubes that are cooled by a continues flow of 150 C cold water from the chiller. The outer shell of heat exchanger is made of Φ55 mm outer diameter, thickness of 5 mm and length 30 mm. Holes of 4 mm have been drilled equally on two circular plates and baffles of 45 mm in diameter with each 3 mm thickness. The bottom flange of hot end heat exchanger is fixed to top flange of vacuum chamber with O-ring seal and nut-bolt arrangement.



E. Reservoir or Buffer

The reservoir or buffer is mainly used to stabilize pressure oscillations of the system where gas comes out from the orifice. It helps to keep the gas pressure more or less constant. The reservoir is made of stainless steel with a volume of 3 liters. A schematic view of reservoir is shown in Fig.3.11.

Fig.3.11 Photographic view of Reservoir

F. U-tube

It is a passage connecting regenerator and pulse tube where helium flows smoothly between them. The U-tube that connects the regenerator and pulse tube is of soft copper tube with external diameter of 12 mm and thickness of 1 mm is shown in Fig.3.12.

Fig.3.12 Photographic view of U-tube

IV. CONSTRUCTION OF EXPERIMENTAL TEST-RIG

A. Introduction

Though the theoretical and analytical investigations on pulse tube refrigerator have been carried out from early stage of its invention and continue till date, the most of work is primarily experimental investigation; which plays a very prominent role in its development. The double inlet pulse tube refrigerator system consists of a compressor, regenerator, pulse tube, reservoir, heat exchanger and the valve system. This chapter gives a detailed construction and other components required for the experimental setup.

B. Experimental Technique

Experimental studies on the three common types (BPTR, OPTR and DIPTR) of the pulse tube refrigerator have been investigated in the present work. The present objective of the study is to develop the design technology of pulse tube refrigerator and find out its optimum operating condition and its performance with respect to various operating conditions. As a preliminary test, the refrigeration performance of the basic, orifice and double inlet pulse tube refrigerators has been investigated according to their cooling behavior and minimum attainable temperature at no load condition. The important studies made are listed below along with their objectives.

- Cool down behaviour of the system

It is required to investigate the cool down behaviour of the system to know the required time for reaching the equilibrium state.

- Effect of pressure ratio

Performance of pulse tube cooler is strongly dependent on the pressure ratio i.e. the ratio of highest to lowest pressure because this parameter determines the range of compression and expansion work and fluid characteristics inside the system.

- Effect of flow resistance

Performance variation of the different pulse tube refrigerators are mainly due to phase relationship between the pressure and mass flow in the system. This is achieved with the help of flow resistance devices i.e. orifice and double inlet valves and controlling their opening. To determine the optimum operating condition, data has been taken at different opening of the valves.

- Performance comparison

Comparison among the different types of pulse tube refrigerators (BPTR, OPTR and DIPTR) has been conducted at various pressures, valve openings and at different cold end temperatures.

The indigenously developed pulse tube refrigerator test rig consists of several sub systems such as compressor, rotary valve, regenerator, pulse tube, hot end heat exchanger, flow resistance valves, reservoir or buffer and a U-tube. A vacuum pumping system has been used to provide thermal insulation outside the pulse tube system. The schematic of the experimental set up has been shown in Fig.4.1. All the accessories have been discussed separately along with their specifications, design criteria and fabrication. The experimental test rig has been made in such a way that it can be operated as basic, orifice as well as double inlet type to facilitate the requirement of comparative study among them.

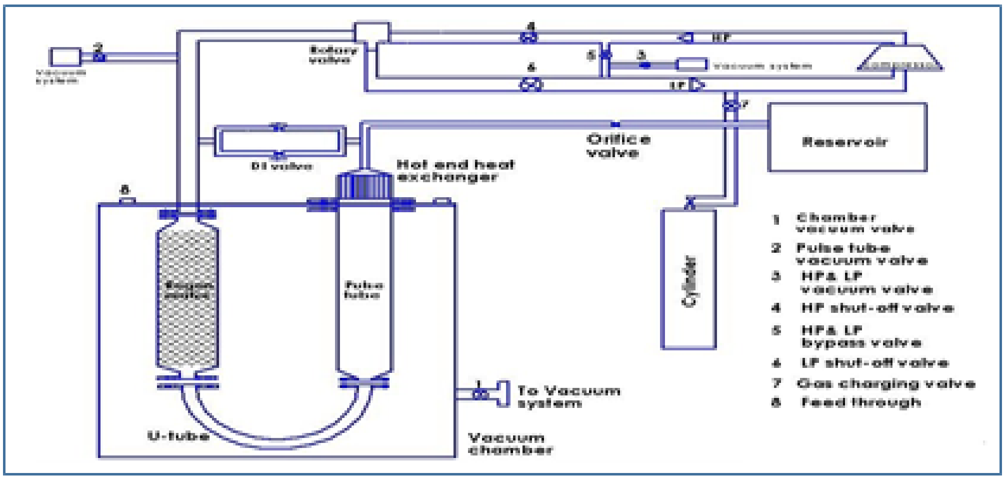


Fig.4.1 Schematic view of Experimental set-up

The test set-up has been designed and developed for a scroll compressor of power 8 kW. But it has been tested successfully with a reciprocating helium compressor of power 1.5 kW. The performances and its effects have been discussed in chapter 5.

Fig.4.2 Experimental test-rig of Pulse Tube Refrigerator

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

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.

A. Cooling behaviour

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 (approx.). Figures of (5.1 to 5.6) 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.

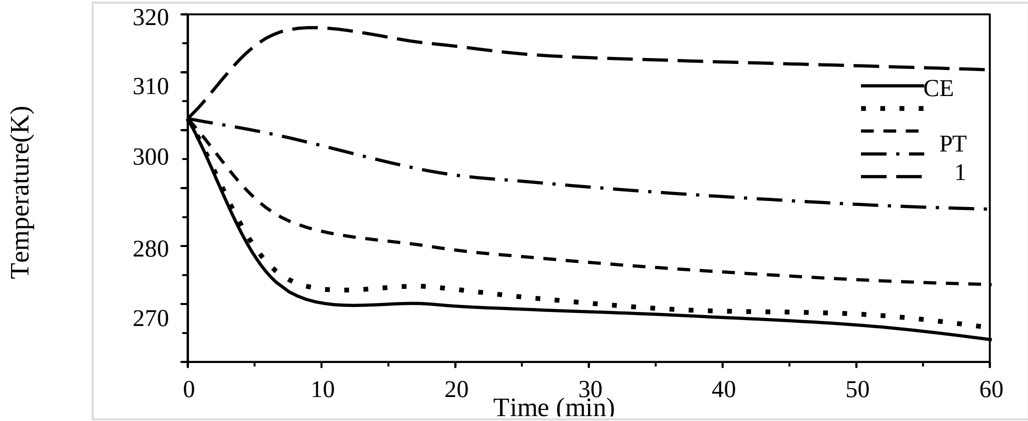


Fig.5.1 Cool down behaviour at optimum opening of orifice valve at HP =10 bar and LP=8 bar at no load as OPTR

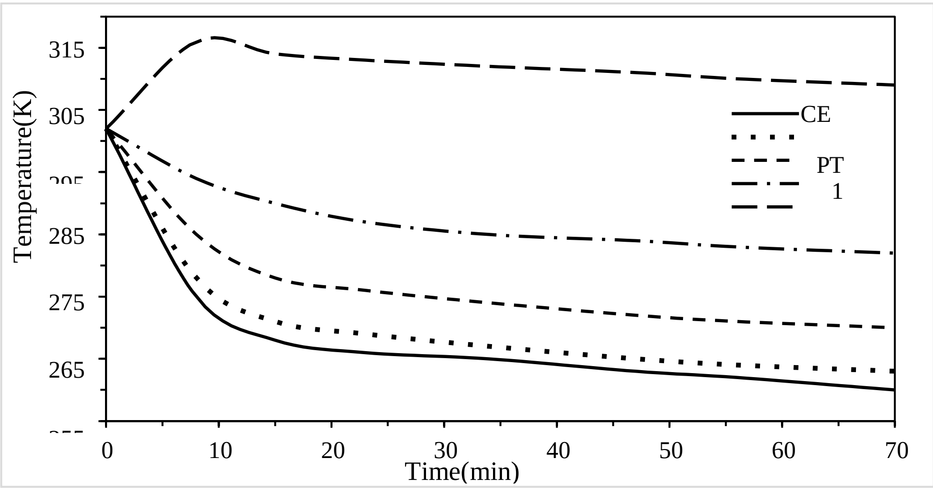


Fig.5.2 Cool down behaviour at optimum opening of double inlet valve at HP =10 bar and LP=8 bar at no load as DIPTR.

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.

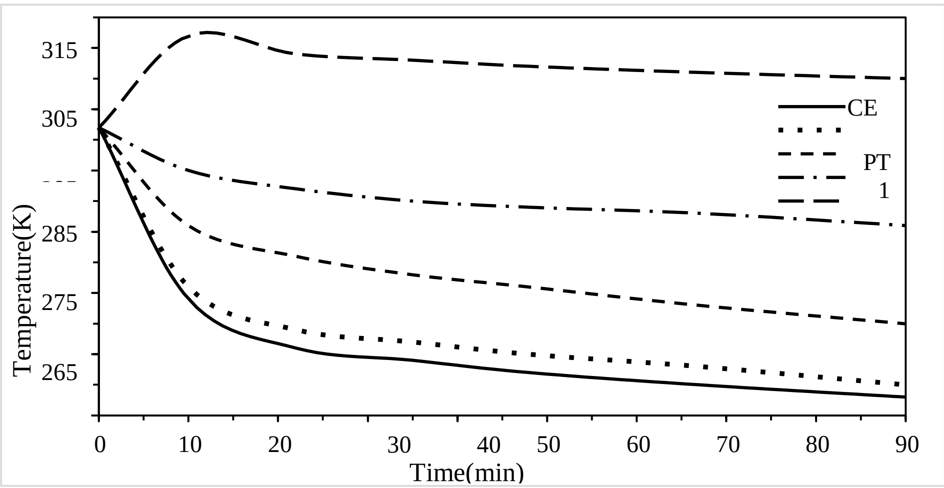


Fig.5.3 Cool down behaviour at optimum opening of double inlet valve at HP =14 bar and LP=10 bar at no load as DIPTR

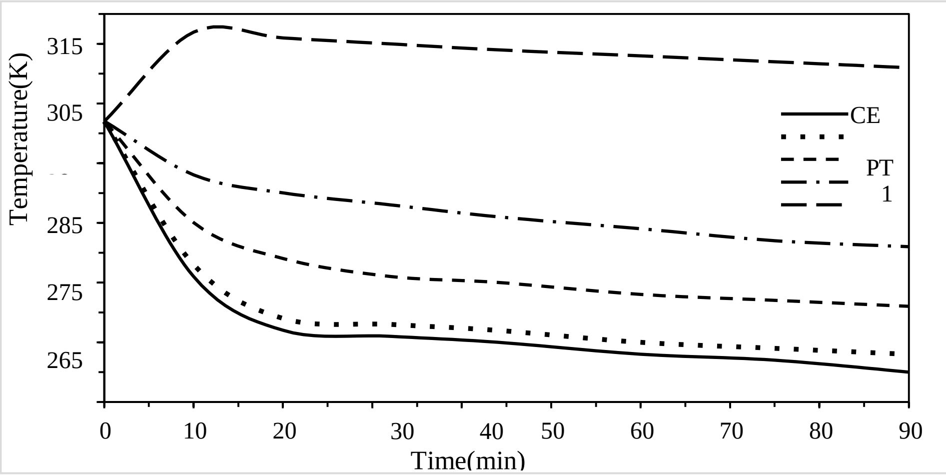


Fig.5.4 Cool down behaviour at optimum opening of orifice valve at HP =14 bar and LP=10 bar at no load as OPTR.

The experimental set-up when operated as a double inlet type achieved a lowest temperature of 258 K at an optimum opening of double inlet valve at 0.197 inches and of orifice at 0.152 inches at a high pressure of 14 bar and low pressure of 10 bar. At same pressure when operated as an orifice type a lowest temperature of 259 K has been obtained at an optimum opening of orifice at 0.158 inches.

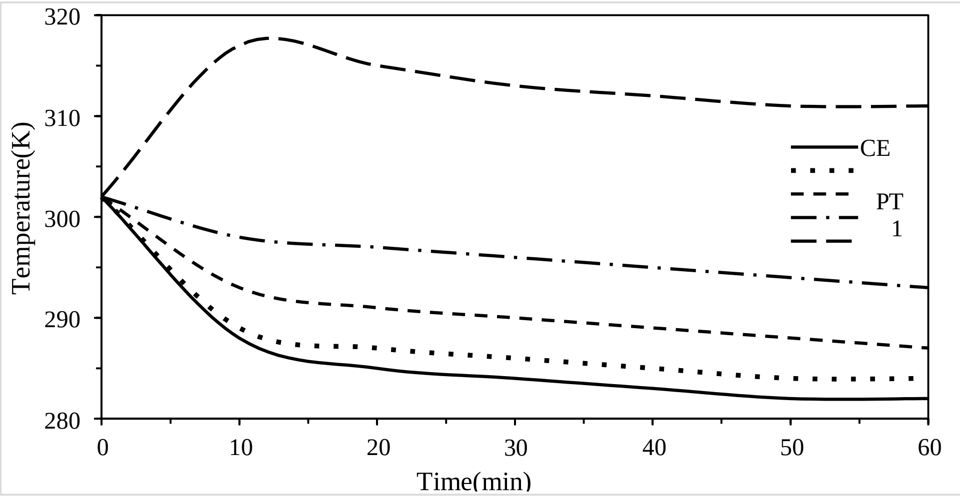


Fig.5.5 Cool down behaviour of BPTR at HP =10 bar and LP=8 bar at no load

Temperature(K)

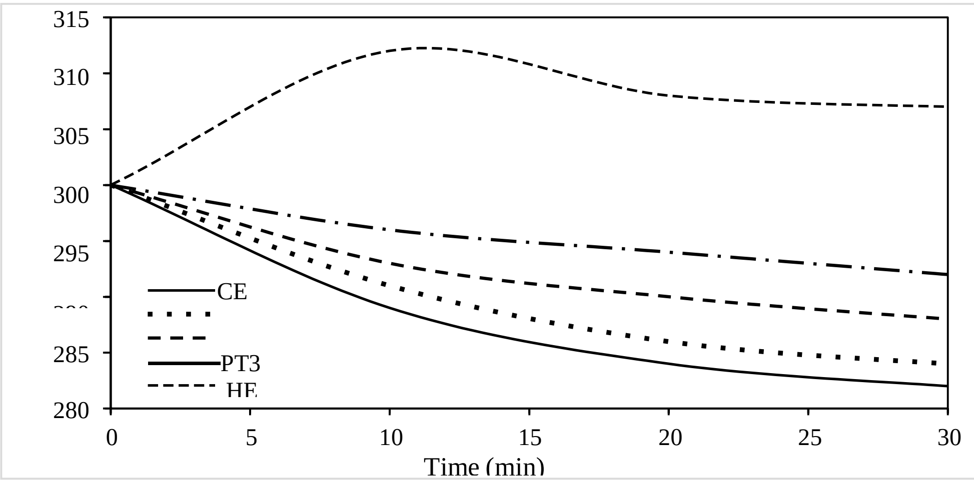


Fig.5.6 Cool down behaviour of BPTR at HP =10 bar and LP=5 bar at no load

Form the figures (5.5 and 5.6), it has been observed that BPTR is inefficient and less effective in terms of cool down behaviour irrespective of operating pressure and valve openings.

VI. CONCLUSION

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. Summary

- 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.
- The lowest temperature at the cold end has been obtained in this case. It has found that at 0.197 inches opening of double inlet valve and orifice at 0.152 inches are optimum opening for double inlet type.
- Observed that 0.158 inches is the optimum opening for orifice type. Optimization of the valves opening has been carried out at different average pressures of the system.
- Pressure variations of the pulse tube system have been determined at different orifice and double inlet opening. Pressure variations at various positions such as regenerator inlet, pulse tube and at reservoir in the experimental set-up have been shown.
- The pulse tube refrigerator plant has been successfully commissioned.

B. Scope of future work

This chapter does not mark the end of our venture; rather we can say that it is the beginning of a major endeavor that has been initiated. Naturally, there are lots of activities left behind. In spite of these studies, there are several possible issues considered for future research work. 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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