Performance Investigation of Pulse Tube Refrigerator with Different Regenerative Material

By

Krunal R. Parikh

12MMET16

DEPARTMENT OF MECHANICAL ENGINEERING

INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY

AHMEDABAD-382481

May 2014

Performance Investigation of Pulse Tube Refrigerator with Different Regenerative Material

Major Project Report

Submitted in partial fulfillment of the requirements

For the Degree of

Master of Technology in Mechanical Engineering (Thermal Engineering)

By

Krunal R. Parikh

(12MMET16)

Guided By

Prof. B. A. Shah

DEPARTMENT OF MECHANICAL ENGINEERING

INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY

AHMEDABAD-382481

May 2014

Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering (Thermal Engineering) at Nirma University and has not been submitted elsewhere for a degree or diploma.

2. Due acknowledgment has been made in the text to all other material used.

Krunal R. Parikh

12MMET16

Undertaking for Originality of the Work

I, **Krunal R. Parikh**, Roll No. **12MMET16**, give undertaking that the Major Project entitled "**PERFORMANCE INVESTIGATION OF PULSE TUBE REFRIGERATOR WITH DIFFERENT REGENERATIVE MATERIAL**" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering (Thermal) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

Signature of Student

Date:

Place: Nirma University, Ahmedabad.

Endorsed by

(Signature of Guide)

Certificate

This is to certify that the Major Project Report entitled "**Performance Investigation of Pulse Tube Refrigerator with Different Regenerative Material**" submitted by **Mr. Krunal R. Parikh (12MMET16)**, towards the partial fulfillment of the requirements for the award of Degree of **Master of Technology in Mechanical Engineering (Thermal Engineering)** of Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination.The result embodied in this major project, to the best of our knowledge, has not been submitted to any other University or Institution for award of any degree.

Prof. B. A. Shah
Assistant Professor and Guide,
Department of Mechanical Engineering,
Institute of Technology,
Nirma University,
Ahmedabad.

Dr. R. N. Patel
Professor and Head,
Department of Mechanical Engineering,
Institute of Technology,
Nirma University,
Ahmedabad.

Dr K Kotecha
Director,
Institute of Technology,
Nirma University,
Ahmedabad.

Acknowledgments

I would like to give my special thanks to my faculty guide, **Prof. B. A. Shah**, Assistant Professor, Department of Mechanical Engineering, Institute of Technology, Nirma University, Ahmedabad for his valuable guidance and continual encouragement throughout the project work.

I am very much thankful to **Dr. R. N. Patel** (Head of Dept. of Mech. Engg., Institute of Technology, Nirma University) and **Dr K Kotecha** (Director, Institute of Technology, Nirma University) who have directly or indirectly helped me during this dissertation work.

I am obliged to my family specially my parents for love and support and also my colleagues for their many suggestions, constant support and motivate me throughout this course, I am thankful to them.

Krunal R. Parikh

12MMET16

Abstract

Cryocooler is a device which is used to produce low temperature by compression and expansion of the gas. In the last few years there has been increasing demand of cryocoolers for cooling of infrared sensors used on satellite and in tanks, missiles, high temperature super conductors, low noise amplifiers, superconducting quantum interference devices etc.

As pulse tube refrigerator has no moving parts in its cold section, and when driven by a liner compressor, has the potential of achieving higher reliability and lower vibrations than other cryo refrigerators (cryocoolers). The performance of a pulse tube refrigerator is depend on the type of the configuration of pulse tube refrigerator and frequency of the working gas. In addition, the performance is also depends on regenerator material and the matrix of that material which is used in pulse tube refrigerator as well as on pressure drop through regenerator.

The regenerator is one of the most important components of the pulse tube refrigerator. To achieve better performance of regenerator, regenerator materials should be properly selected, normally phosphor bronze, stainless steel, lead and copper are used as regenerator materials, to achieve low temperature.

Main objectives of this dissertation work is to obtain no load characteristic of pulse tube refrigerator with different regenerative materials like S.S. and phosphor bronze with different wire mesh size for basic pulse tube refrigerator, orifice pulse tube refrigerator and double inlet pulse tube refrigerator.

In Chapter 1 the brief review of the introduction of cryogenics and pulse tube refrigerators is given. Evolution of pulse tube refrigerators and review of analytical, experimental, CFD work reported in the literature, brief of regenerative materials and objective of present work is given in Chapter 2 . Various components used in the experimental test setup and operation instructions for BPTR, OPTR and DIPTR have been described in Chapter 3. Chapter 4 includes the results obtained by varying different parameters like cycle time, regenerative materials and its wire mesh size have been given. In Chapter 5 the conclusions & future scope of work has been explained.

Contents

List of Figures

List of Tables

Abbreviation & Nomenclature

PTR	Pulse tube refrigerator
$OPTR$	Orifice pulse tube refrigerator
$BPTR$	Basic pulse tube refrigerator
$IPTR$	Inertance pulse tube refrigerator
$TAPTR$	Themoacoustic pulse tube refrigerator
CFD	Computational fluid dynamics
T_a	Room temperature
T_c	Refrigeration temperature
L	Length
D, d	Diameter
l	Length of regenerator
V	Volume
P	Pressure
m	Mass flow rate
T	Temperature
N	No. of cycle per min
τ	Cycle time
A	Area
μ	Viscosity
G	Mass velocity
C_p	Specific heat
R	Universal gas constant
k	Thermal conductivity
α	Specific surface of wire
ϕ	Porosity of regenerator
β	Opening area ratio
p	Pitch

Subscript

t	Pulse tube
r	Regenerator
l	Lower
h	Higher
c	Cold
h	Hot
w	Wire

Chapter 1

Introduction

1.1 General

Cryogenics is basically a Greek word which is combination of kryos and genes. Kryos means very cold or freezing and genes means to produce. Cryogenics is the science and technology which deals with the phenomena that occur at very low temperature, nearer to the lowest theoretically possible temperature. In engineering, cryogenics can be best defined as an application which operates in the temperature range from 0 K (-273°C) to about 123 K (-150°C). In particular, this includes liquefaction, refrigeration, transport and storage of cryogenic fluids, cryostat design and the study of phenomena that occur at these temperatures.

Cryocooler is a refrigeration machine with refrigeration temperature below 123 K and it has small refrigeration capacity. According to the classification by Walker (1983) there are mainly two types of cryocoolers: regenerative type & recuperative type. The former includes the Brayton cryocooler & the Joules Thomson cryocooler. The latter includes the Stirling type cryocooler and the Gifford-McMahon type cryocooler. These cryocoolers as introduced by Radebaugh (1995), are mainly used for cooling of superconductors and semiconductors, as well as in the the infrared sensors, in the missile guided system and satellite based surveillance . The cryocoolers can also be used in other applications such as in cryopumps, cooling of radiation shields, liquefying natural gases, SQUID (super conducting quantum interference device), Magnetometers, Semiconductor fabrication, SC Magnets etc.

1.2 Classification of Cryocoolers

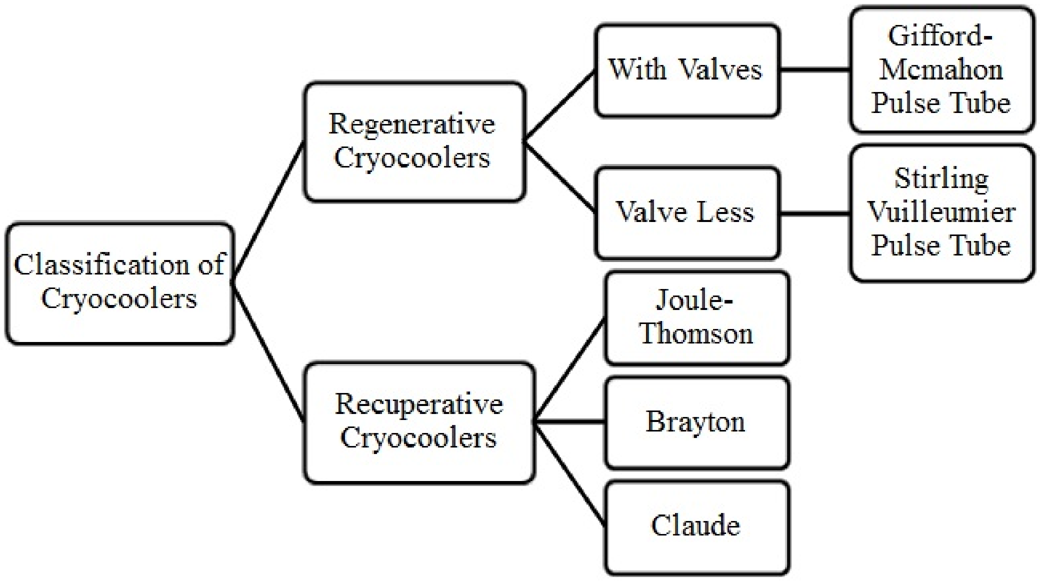

Figure 1.1: Classification of cryocoolers[1]

1.3 Applications of Cryocoolers

Some of the applications of cryocoolers are summarized below [2].

- Gamma-ray sensors for monitoring nuclear activity
- Infrared sensors
- Superconducting magnets for mine sweeping
- Liquefaction of gases
- Cryopumps for semiconductor fabrication
- Super conductors
- Cryogenic catheters & cryosurgery
- Storage of biological cells and specimens
- Agriculture and Biology

Because of these kind of special applications it is important to improve reliability, COP, and reduce weight, size, vibration. Regenerative type heat exchangers have small heat transfer loss therefore it is used in cryocoolers.

Mainly there are two types of cryocoolers. Gifford-McMahon type and Stirling type cryocoolers. In Stirling and GM type cryocooler there is a expansion device to maintain the mass flow rate of the working gas but this kind of parts reduce the reliability of the cryocooler. Pulse tube refrigerator (cryocooler) has no moving part in the cold end it has reliability, long life low vibration. Therefore it is important to improve the pulse tube refrigerator.

1.4 Pulse Tube Refrigerator

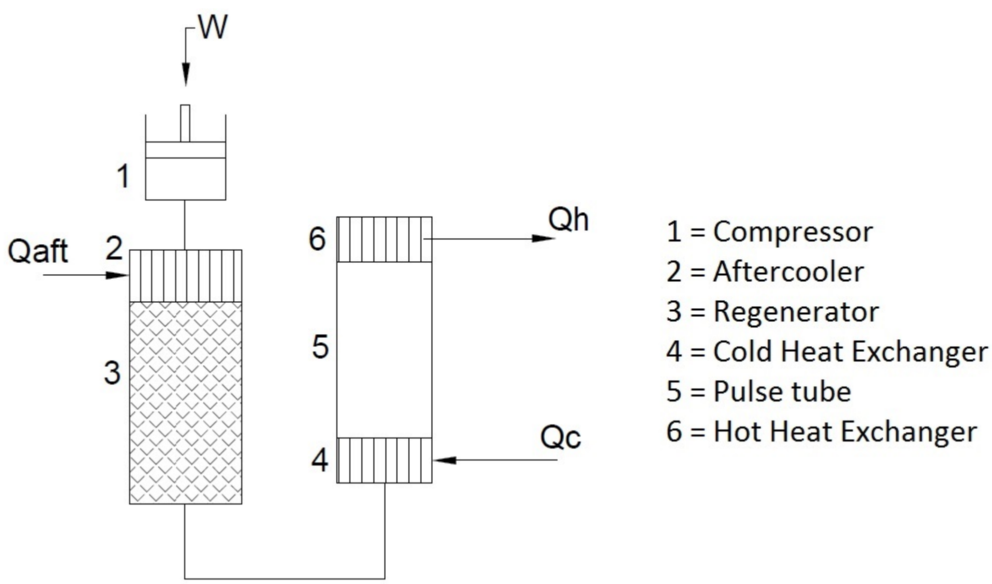

Figure 1.2: Pulse tube refrigerator [1]

Gifford and McMahon [3] observed that there is a cooling produced in the hollow tube because of the pulsating effect. And that was the simple pulse tube refrigerator. Nowadays it is known as basic pulse tube refrigerator (BPTR). There is no moving part in the cold region so it is most important to improve cryogenic refrigeration. Main advantage of the pulse tube cryocooler is low vibration so that it has long life.

1.5 Principal of Working

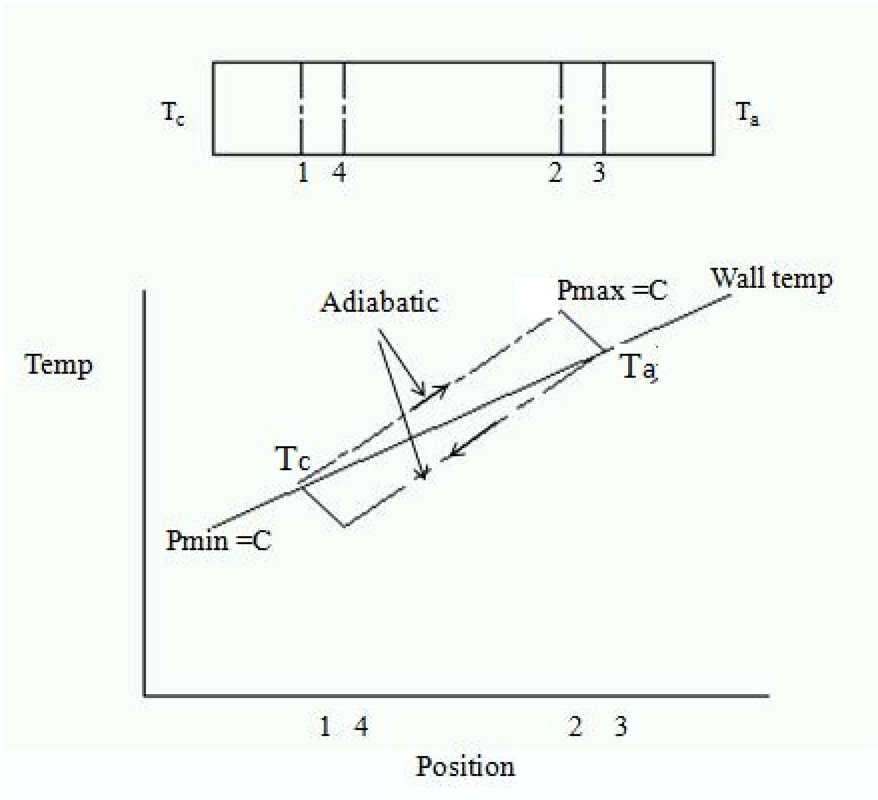

Figure 1.3: Principal of working [3]

Pulse tube refrigerator works on the principal of surface heat pumping which is shown in Fig. 1.3.

1. Process 1-2 adiabatic compression

Because of the pressure difference gas which was compressed in the compressor it works as a piston and compress the gas in the pulse tube and this process increase the temperature of the gas.

2. Process 2-3 constant high pressure cooling

In process 1-2 gas temperature increased compare to the wall temperature hence in this process gas is being cooled by the heat exchanger and temperature becomes T_a, which produces the refrigeration effect during the expansion process.

3. Process 1-2 adiabatic expansion

In process 3-4 piston moves up and produces pressure difference in the system therefore it produce adiabatic expansion of the gas with the drop in temperature to the wall temperature thus it produce the cooling effect during the low pressure, gas which leaves the pulse tube during this process it also colder than heat exchanger, which provides cooling for thermal load at T_c in the heat exchanger.

4. Process 4-1 Constant low pressure heating

In this process the gas which was expanded is warmed at constant low pressure by cooling the wall and providing the refrigerating effect in the heat exchanger.

- **Temperature v/s displacement**

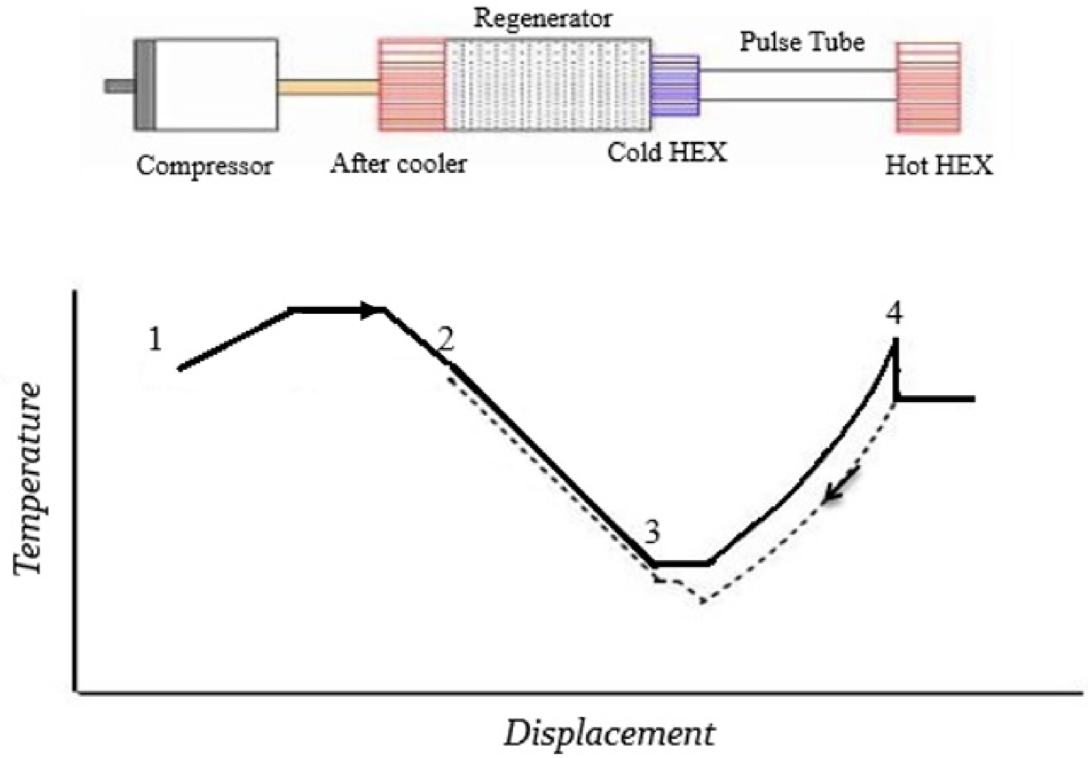

Figure 1.4: Temperature v/s displacement [3]

Temperature distribution with respect to displacement is shown in the Fig. 1.4.

1. At point 1

Temperature of the working gas will increase because of the compression process in the compressor. And it will pass to the after cooling through connecting pipe. In connecting line the temperature will be constant. Then the gas will reach at the after cooler. In after cooler temperature will be decrease because of the heat transfer between water and gas.

2. At point 2

In regenerator heat and/or cold of the working gas will absorb and stored for the next cycle.

3. At point 3

After the regenerator temperature of the compressed gas will decrease and it flows to the pulse tube. Pulse tube is the hollow tube and it has some residual air. Compressed gas will apply the pressure to the air so residual gas will compressed therefore the temperature of air will increase.

4. At point 4

After the residual air will compressed, temperature will increase. At 4 it is cooled with the water in the water jacket therefore the temperature will decrease. And the gas will return to the regenerator after the expansion in the pulse tube. Because of the expansion temperature will further decrease.

Chapter 2

Literature Review

2.1 Introduction

This chapter represents a review of the literature. It can be broadly classified under five main categories. The first part of the survey deals with the classification of pulse tube refrigerators. Theoretical investigations on pulse tube refrigerators has been explained in second part, the third part deals with experimental investigations on pulse tube refrigerators, the forth part deals with the CFD investigation on the pulse tube refrigerator. Regenerative materials has been explained in fifth part.

2.2 Classification of Pulse Tube Refrigerators (PTRs)

There are many ways of classifications of pulse tube refrigerator.

1. Based on nature of pressure wave generator:

    - Stirling type PTRs
    - Gifford McMahon type PTRs

2. Based on geometric configuration:

    - Basic Pulse Tube Refrigerator (BPTR)
    - Orifice pulse tube refrigerator (OPTR)
    - Double inlet pulse tube refrigerator (DIPTR)
    - Inertance tube pulse tube refrigerator (ITPTR)
    - Multiple inlet pulse tube refrigerator

- Active buffer type pulse tube refrigerator
- Multi stage pulse tube refrigerator
- Thermoacoustic pulse tube refrigerator (TAPTR)

3. Based on arrangement of pulse tube and regenerator:

- U type pulse tube refrigerator
- In-line type pulse tube refrigerator
- Coaxial type pulse tube refrigerator

Following is the brief about all above pulse tube refrigerators:

- **Stirling type pulse tube refrigerator**

Stirling type pulse tube is shown in Fig. 2.1, a piston cylinder apparatus is directly coupled to the hot end of the regenerator so that the pressure fluctuations are directly generated by the piston movement.

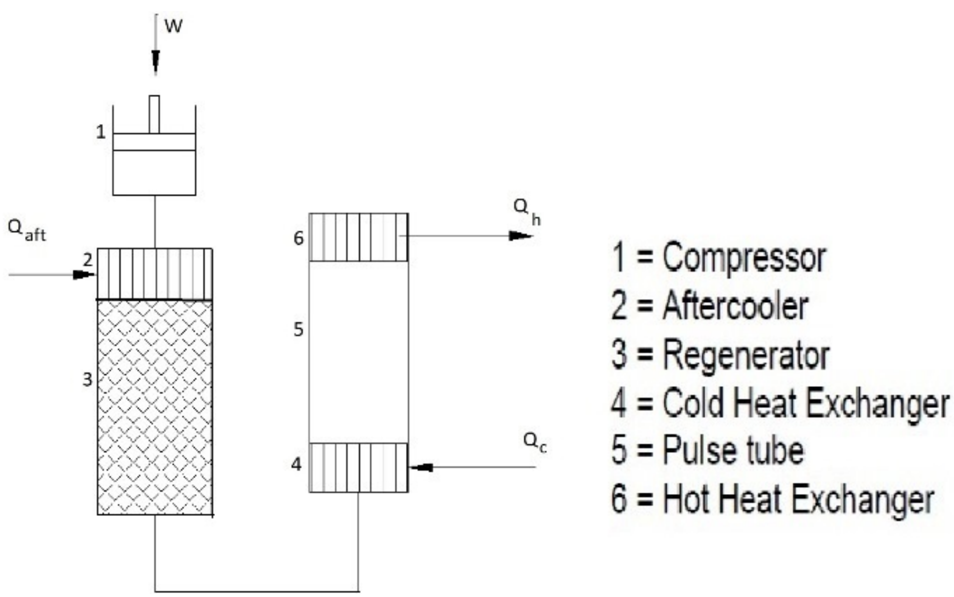

Figure 2.1: Stirling type pulse tube refrigerator[1]

For a Stirling type pulse tube as shown in Fig. 2.1, a piston cylinder apparatus is connected to the system so that the pressure fluctuations are directly generated by the piston movement. The typical operating frequency is 10 to 100 Hz, higher than that of a G-M type pulse tube. Because of this high operating frequency and the absence of valve losses, Stirling type pulse tube systems generally produce higher cooling powers than G-M type pulse tubes. However, the rapid heat exchange required in Stirling type pulse tube refrigerators limits their performance at lower temperatures, such as 10 K and below.

- **G-M type pulse tube refrigerator**

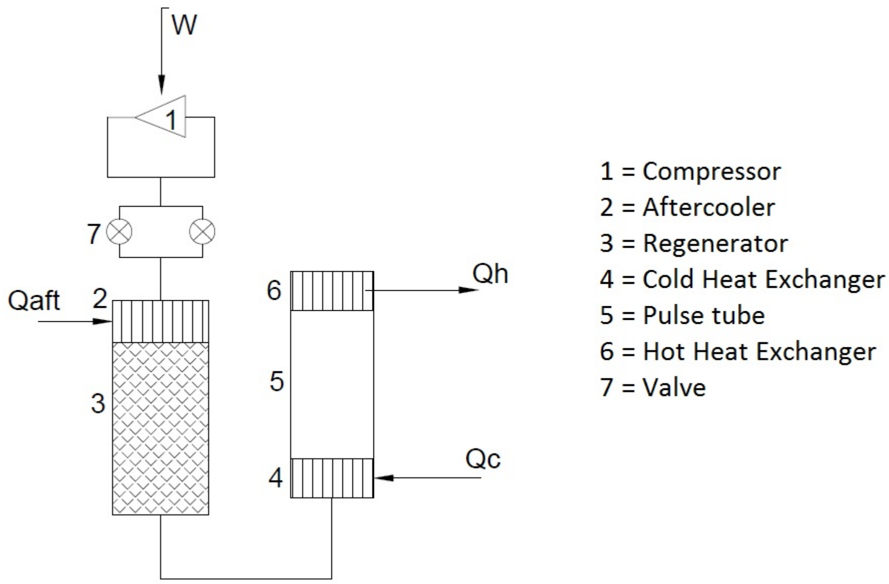

Figure 2.2: G-M type pulse tube refrigerator [1]

The G-M type pulse tube refrigerator which is shown in Fig. 2.2. By using valve systems it supplies high or low pressure gas into the pulse tube. The pressure pulsation in the system is produced by opening and closing of the valve opening and closing. G-M type pulse tube operates at very low frequencies. The valve system devises compressor and pulse tube therefore vibration in the pulse tube refrigerator is very less.

- **Basic Pulse Tube Refrigerator (BPTR)**

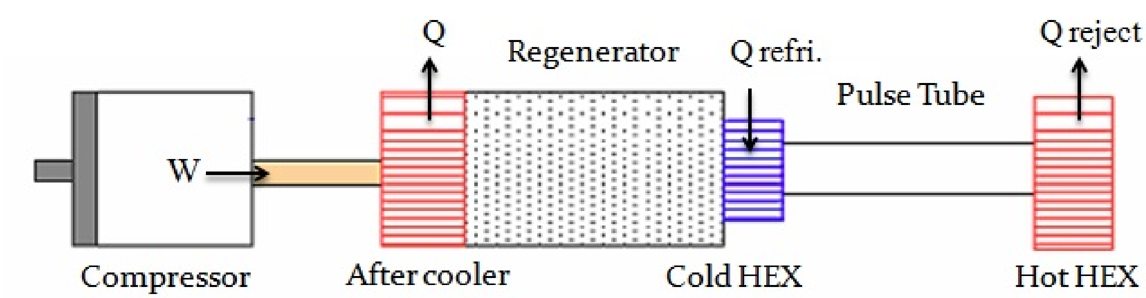

Figure 2.3: Basic pulse tube refrigerator (BPTR) [4]

It is the first pulse tube which was built in 1963 by Gifford and Longsworth [3]. Its basic components are regenerator, pulse tube, pressure wave generator, and two heat exchangers as shown in Fig. 2.3. The pulse tube is a simple tube which has one open end and one closed end. The closed end is the hot end which capped with a heat exchanger that cools it to the ambient temperature with the help of water. The open end which is cold end is connected to the regenerator which is a second heat exchanger. The regenerator is a periodic flow heat exchanger which absorbs heat from gas pumped into the pulse tube pre-cooling it, and stores the heat for half a cycle then transfers it back to outgoing cold gas in the second half of the cycle cooling the regenerator. The interior of the regenerator tube is filled with either packed spheres or stacked fine mesh screens to increase its heat capacity. A piston, compressor or similar pressure wave generator is attached to the warm end of the regenerator and provides the pressure oscillations that provide the refrigeration. Generally Helium is used as the working gas due to its monotonic ideal gas properties and low condensation temperature. In systems with a base temperature below 2K the 3He isotope is used. Record low temperatures achieved with this basic pulse tube design are 124 K with a single stage and 79 K using two stages [5].

- **Orifice Pulse Tube Refrigerator (OPTR)**

Mikulin et. al. was the modified in basic pulse tube refrigerator and added a small orifice valve at the warm end of the pulse tube in 1984, An orifice is just a needle valve or throttle valve to regulate flow. Their new design had a base temperature of 105 K [6].

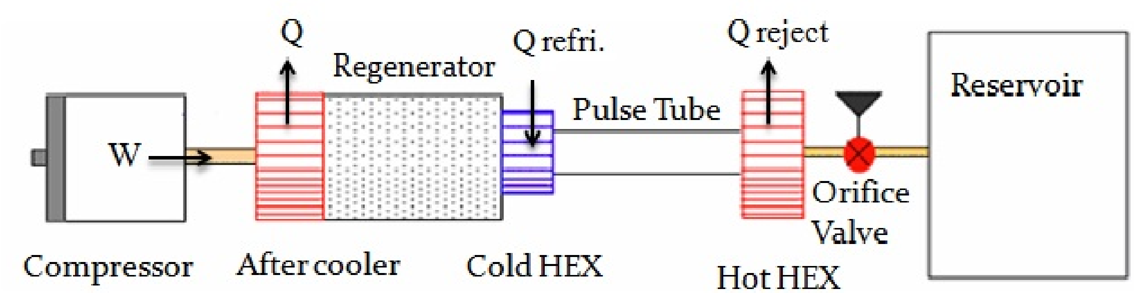

Figure 2.4: Orifice pulse tube refrigerator (OPTR)[4]

And Radebaugh et. al. further improved the design, by arranging the orifice outside the heat exchanger and added a reservoir after the orifice. The reservoir is large enough to be maintained at nearly constant intermediate pressure during experiment. This design reached a temperature of 60 K [5]. This new design is responsible for increase in efficiency. It is due to addition of small orifice causes improve in phase between velocity and temperature as a result more enthalpy flow near hot heat exchanger. Such types of refrigerator are known as Orifice Pulse Tube Refrigerator (OPTR) which is shown in Fig. 2.4. The disadvantage of the orifice pulse tube is that a large amount of compressed gas which produces no actual refrigeration, it has to flow through the regenerator. This reduced the refrigeration power per unit of compressed mass and hence increases the regenerator loss. The increase in mass flow rate in the regenerator reduces the effectiveness of the regenerator, and increase the pressure loss. Both of these effects reduced performance of OPTR.

- **Double Inlet Pulse Tube Refrigerator (DIPTR)**

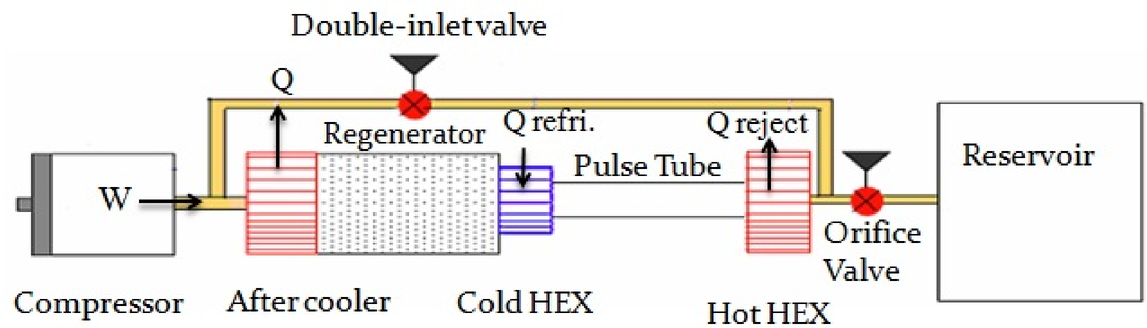

Figure 2.5: Double inlet pulse tube refrigerator (DIPTR)[4]

The efficiency of the pulse tube refrigerator can be increased by maximizing the refrigeration power per unit mass flow. The extra gas, even though it provides no refrigeration power, but it must be cooled by the regenerator which increases the heat transfer load but does not work and therefore limits refrigeration. Zhu, Wu and Chen addressed this problem by adding a direct connection, or secondary orifice, between the warm end of the regenerator and the warm end of the pulse tube [7]. This is known as double inlet pulse tube refrigerator (Fig. 2.5). The secondary orifice is designed as it allow about 10% of the gas, which does not contribute to refrigeration, to travel directly from the pressure oscillator to the warm end of the pulse tube, bypassing the regenerator pulse tube arrangement. This direct flow compresses and expands the warm working gas in the pulse tube, and reduces the amount of gas that needs to be pre-cooled by the regenerator. The extra gas flow also regulates the phase angle between the pressure and mass flow in the system.

- **Inertance Tube Pulse Tube Refrigerator (IPTR)**

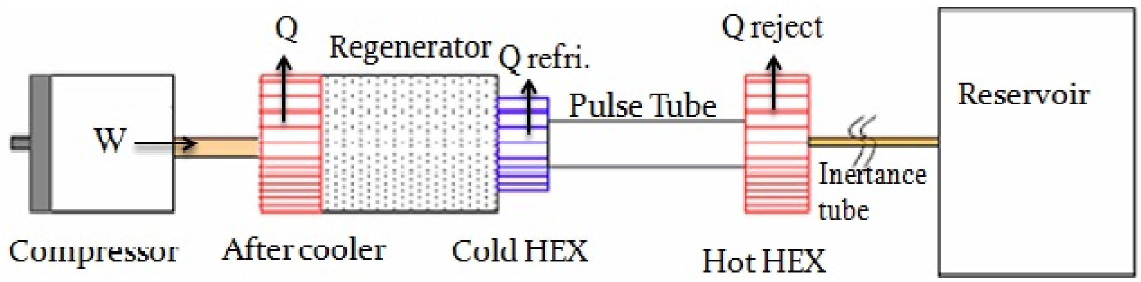

Figure 2.6: Inertance tube pulse tube refrigerator (IPTR)[1]

A possibility to avoid the DC-flows, but to maintain an improved cold side phase angle, is the use of an inertance tube. This inertance tube which have small diameter, replaces the orifice. In the Inertance Pulse-Tube Refrigerator (IPTR) which is shown in Fig. 2.6, the inertia of the gas is of key importance. Hence, it requires large mass flows or high frequencies. Studies show that use of the inertance tube is beneficial for large-scale pulse tubes operating at higher frequencies.

- **Multiple-inlet type PTR**

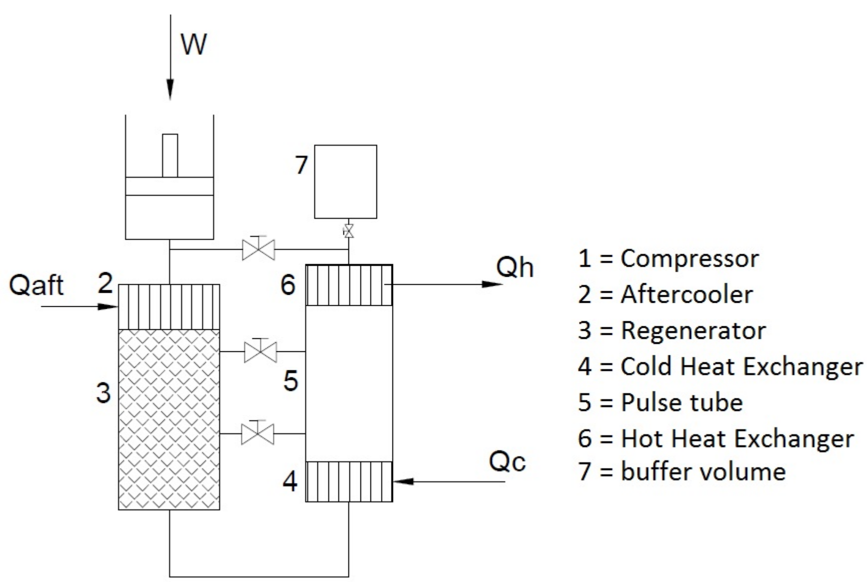

Figure 2.7: Multiple-inlet type pulse tube refrigerator[1]

In this type of PTR some points in the regenerator which have temperature difference is connected to some points in the pulse tube. Fig. 2.7 shows schematic diagram of the multiple inlet type PTR. There is a distribution of the gas in the regenerator and pulse tube therefore it helps to improve the performance.

- **Active buffer PTR**

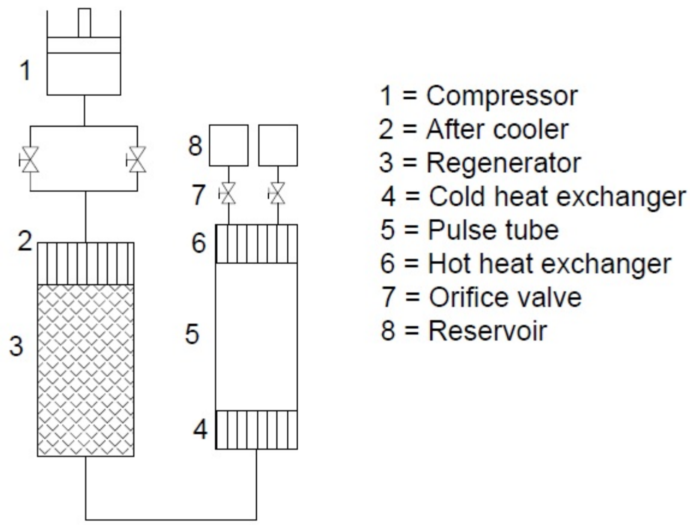

Figure 2.8: Active buffer PTR[1]

Fig. 2.8 gives the schematic diagram of the active buffer PTR. Active buffer type pulse tube refrigerator is the same as the orifice pulse tube but it has more buffer volumes. From that it can help to maintain the mass flow through orifice.

- **Multistage arrangement type PTR**

There is a some specific limit to reach the low temperature in single PTR. This problem can resolved by adding the other refrigerator at the end of the cold end. Now others hot end is become cold end of the first PTR.

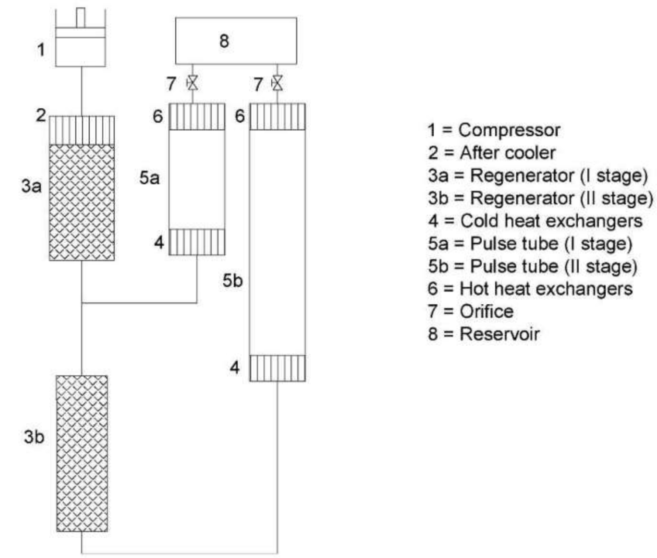

Figure 2.9: Multistage arrangement type PTR[1]

Therefore inlet gas of the pulse tube refrigerator is cold so, it can produce more cooling. Fig. 2.9 shows orifice type multistage type pulse tube refrigerator. Same as the double inlet PTR three-stage PTRs have also been introduced. Three-stage PTR, by using 3He as working gas, lowest temperature 1.78 K has been reached.

- **Thermoacoustic PTR**

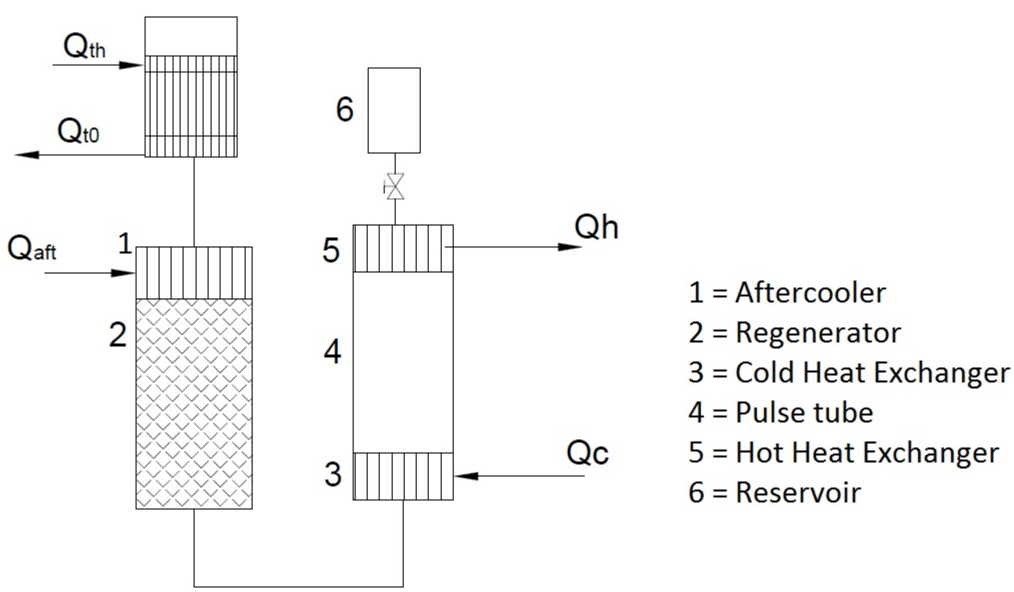

Figure 2.10: Thermoacoustic pulse tube refrigerator[4]

Thermoacoustic refrigerator is also known as resonant pulse tube. This works on the principle of thermo-acoustic pressure wave instead of a mechanical one. The thermoacoustic driver pulse tube refrigerator is shown in Fig. 2.10. It was first demonstrated in 1990 in a joint effort of the NIST and Los Alamos National Laboratories (1990) [8]. It reached a no-load temperature of 90 K and is the first cryogenic refrigerator with no moving parts.

- **U-shape type PTR**

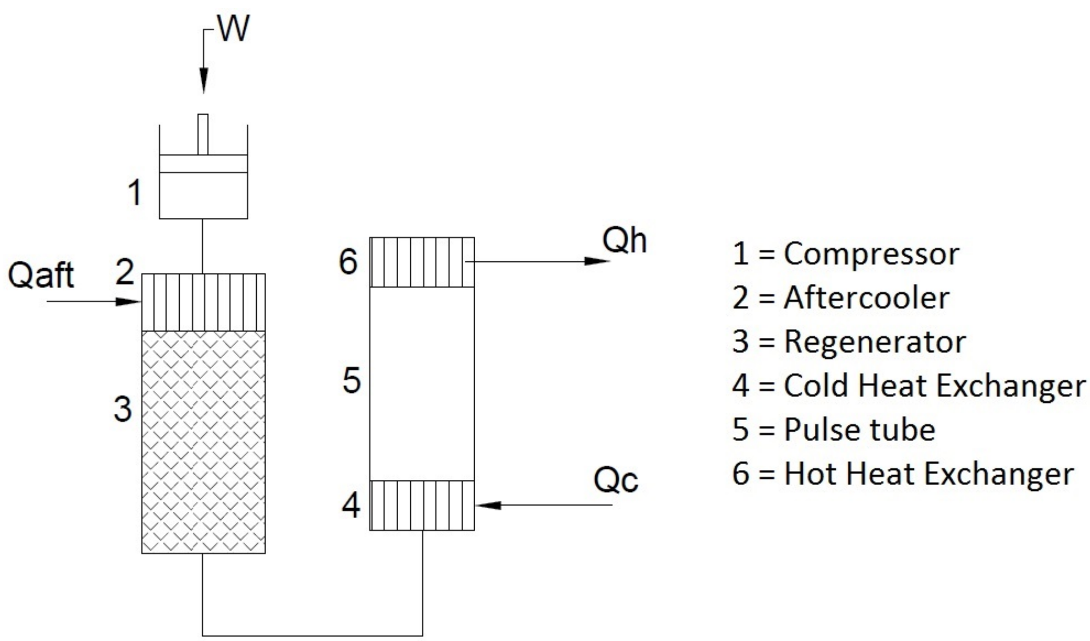

Figure 2.11: U-shape type PTR [1]

Fig. 2.11 shows U type PTR, which is most common shape of PTR. Connecting pipe of the pulse tube and refrigerator is U shaped hence it called U type pulse tube refrigerator. In inline kind of connecting tube cold region is placed in the middle side but in U type it placed at the end side.

- **Linear type PTR**

If the regenerator and the tube are in line as shown in Fig. 2.12, it called a linear PTR.

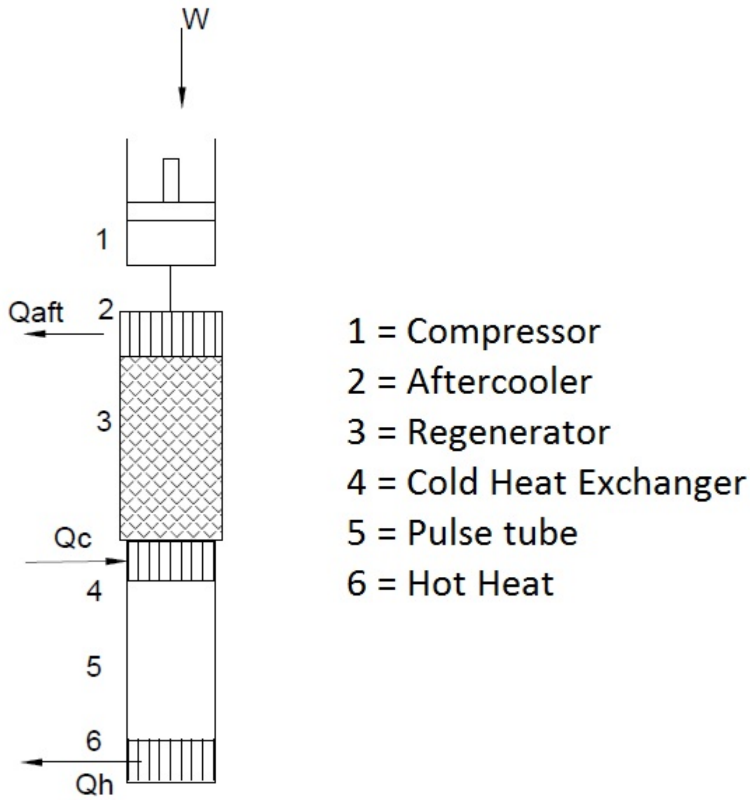

Figure 2.12: Linear type PTR[1]

The best arrangement for mounting the PTR in the vacuum chamber is with the hot end of the tube, where heat is released to the environment, connecting to the vacuum chamber wall. However the cold end of the regenerator is inside the vacuum chamber.

- **Coaxial type PTR**

Fig. 2.13 shows coaxial type pulse tube refrigerator. In this type of arrangement pulse tube is coaxial with the regenerator.

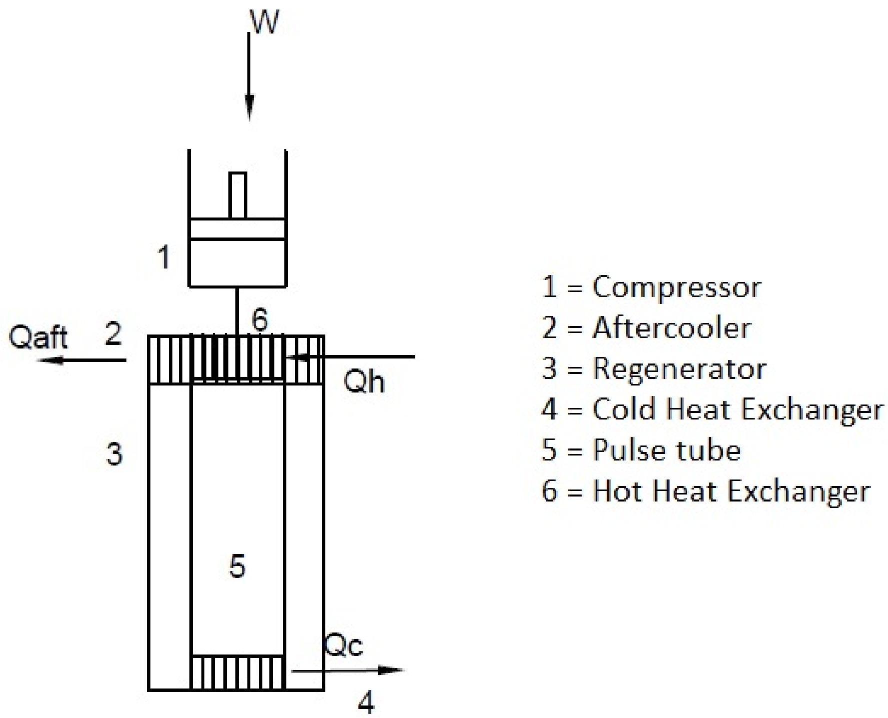

Figure 2.13: Coaxial type PTR [1]

In PTR there is a temperature difference in the regenerator and pulse tube but in coaxial type heat transfer takes place this is the drawback in coaxial type PTR.

2.3 Theoretical Investigation on PTR

Neveu et. al. [9] developed both dynamic and ideal models for better understanding of the entropy and energy flows occurring in the pulse tube refrigerators. Their ideal modeling is sufficient to express the maximum performance, which could be reached, but dynamic modeling is required modification in design.

Y. Kim et. al. [10] presented a start up behavior of the pulse tube refrigerator is experimentally investigated to gain a better understanding of the basic refrigeration mechanism. Two typical types of pulse tube refrigerators which are basic and orifice pulse tube refrigerator are used. It is found that the change of temperature at the very beginning of the oscillation is not adiabatic. Significant differences in the start up behavior between a basic and orifice pulse tube did not appear.

M. Azadi et. al. [11] worked on two dimensional compressible oscillating flows in the tube section of a pulse tube refrigerator system model based on the successive approximation method. The effects of frequency of operation and taper angle on the temperature distribution, time-averaged enthalpy flow, and heat transfer behavior during a cycle are investigated. By increasing the frequency it leads to a higher heat transfer rate in the pulse tube. The enthalpy flow, as the cooling performance representative of the pulse tube, reaches maximum for an optimum convergent taper angle. After studying the temperature distribution and heat transfer process along the axial direction, and the phase behavior of the heat transfer coefficient. The results show that, moving from the cold to the hot end of the pulse tube, the temperature variation domain and heat transfer rate decrease.

The double-inlet valve and inertance tube are the two main phase shifters of pulse tube refrigerators. They are important for the pulse tube refrigerators to obtain an appropriate phase relationship between pressure and mass flow. Hu J.Y. et. al. [12] worked on separate functions of the two phase shifters, inertance tube and double inlet valve numerically and verifies it with experiment. They concluded that the inertance tube cannot provide the optimum impedance for those pulse tube refrigerators with small cooling power because of turbulent flow. In such case, the double-inlet valve can help to provide better impedance and further improve the cooling performance. On the other hand, the inertance tube can provide the optimum impedance for those pulse tube refrigerators with large cooling power and the double-inlet is not necessary in such a cases.

Y.L. Ju et. al. [13] developed and designed, based on theoretical consideration, a new type of 4 K GM/PT hybrid refrigerators. They discussed the influences of different hybrid regenerative materials on the cooling capacity of the new hybrid GM/PT refrigerator.

K.P. Desai et. al. [14] performed phasor diagram, for the orifice pulse tube refrigerator, proposed by Radebaugh. Here the pressure pulse was approximated as cosine function for the analysis .The phasor differences between the dynamic pressure and two mass flow rates viz. At the cold end of the pulse tube and hot end of the regenerator, were calculated using phasor diagram. These phase differences and two mass flow rates were utilized for calculation of refrigeration power, compression power and COP. The effect of frequency, dimension of the pulse tube and regenerator and flow coefficient of orifice valve on the refrigeration power, compression power and COP was studied. The highest COP was found to occur at the frequency of approximate 1.8 Hz.

Razani et. al. [15] developed a thermodynamic model based on exergy flow through pulse tube refrigerators (PTRs). They calculated losses, cooling power, load curves and efficiency. From these data they found out optimum dimensions for PTRs.

Yong et. al. [16] have examined individual loss associated with the regenerator and combined these effects to investigate effects of the size on the performance of stirling cycle cryocoolers. For the fixed cycle parameters and given regenerator length scale, it was found that only for a specific range of the hydrodynamic diameter can produce net refrigeration power and there is an optimum hydraulic diameter at which the maximum net refrigeration is achieved. When the hydraulic diameter is less than the optimum value, pressure drop loss will be high; if the hydraulic diameter is greater than the optimum value, thermal losses will be high.

Richardson [17] explained the influence of viscosity on the surface heat pumping mechanism. It had been shown that miniaturization of the pulse tube is quite feasible provided the effect of viscosity is appreciated.

A two-stage pulse tube refrigerator has a great advantage in that there are no moving parts at low temperatures. But there is a problem of theoretical efficiency, it is very low. The theoretical efficiency is lower than that of a stirling refrigerator. A series two-stage pulse tube refrigerator was introduced by Zhu et. al. [18] for solving this problem. The hot end of the regenerator of the second stage is connected to the hot end of the first stage pulse tube. The expansion work in the first stage pulse tube is part of the input work of the second stage, therefore the efficiency is increased. In a simulation result for a step-piston type two-stage series pulse tube refrigerator, the efficiency is increased by 13.8%.

Improved design of inertance tube type pulse tube refrigerator done by Ki et. al. [19] Through this proposed design which is validate with experimental result cooling capacity of 7 W at 50 K and the Carnot efficiency of 11.7% at 56.3 K was achieved.

The first and second law of thermodynamics was analyze for orifice type and the double-inlet type of pulse tube refrigerator (PTR) by He et. al. [20] by using exergy loss method. Detailed dynamic characteristics of the thermodynamics, flow and heat transfer processes in the PTR were revealed, including the dynamic pressure variations, transient gas temperature, mass flow rate in the PTR. After analysis It was found that the performance coefficient of the double-inlet PTR was 0.108, 9% higher than that of the orifice PTR. The analysis also showed that the exergy efficiency of the DIPTR was 29.95%, significantly higher than that of the orifice PTR (25.04%). In addition, it was found that the exergy losses in the regenerator and orifice were substantially larger than in other components of the PTR system.

2.4 Experimental Investigation on PTR

Qiu et. al. [21] worked on pulse tube refrigerator by changing regenerative material $GdAl_3(GAP)$. Some of the regenerative material as shown in Fig. 2.14. They found that the cooling power and COP of two stage pulse tube cooler below 4 K has been increase gradually by using the newly developed ceramic magnetic regenerative material $GdAlO_3$. Cooling power of 200 mW at 3.13 K, and 400 mW at 3.70 K have been achieved with a compressor input power about

4.8 kW. Result shows that the cooling power near 3 K increased by 150% compared to that same pulse tube cooler employing only conventional $HoCu_2$ and ErNi regenerator material because of their volumetric specific heat difference.

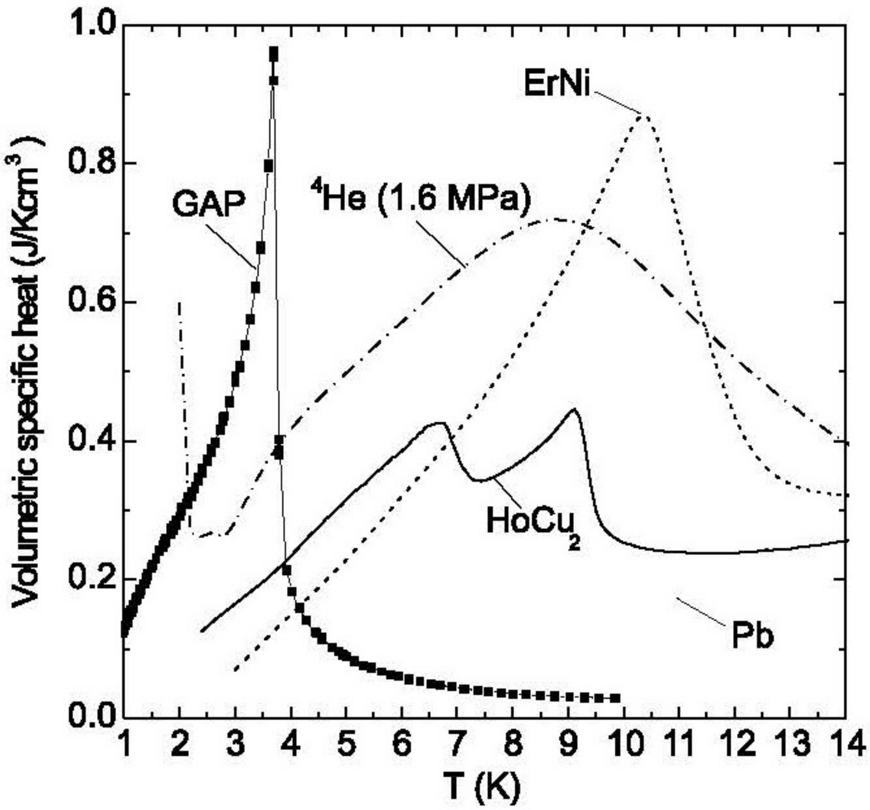

Figure 2.14: Volumetric specific heat of some regenerative material[10]

Xu et. al. [22] worked on pulse tube refrigerator below 2 K. before they worked on 3He other pulse tube refrigerators operating at the liquid helium temperature range use 4He as the working fluid. However, the lambda transition of 4He is a barrier for reaching temperatures below 2 K. Theoretical analysis in this paper shows that, using ^{3}He, the temperature limit is below 2 K, and the efficiency of a 4 K pulse tube refrigerator can be improved significantly. A three stage pulse tube refrigerator is constructed. A compressor with input power of 4 kW and a rotary valve are used to generate the pressure oscillations. With 4He, a minimum average temperature of 2.19 K was reached. Replacing 4He by 3He, at the same valve settings and operating parameters, the minimum average temperature goes down to 1.87 K and the cooling power at 4.2 K is enhanced about 60%. After fine tuning of the valves, a minimum average temperature of 1.78 K was obtained. This is the lowest temperature achieved by mechanical refrigerators.

Wang et. al. [23] are worked on pulse tube refrigerator with 'L' type pulse tube and two orifice valves they conclude that in L type pulse tube big wall thickness affect the lowest temperature of the system and they reach at the lowest temperature of 72 K at 2.5 Hz frequency.

There is a shuttle loss occurred in pulse tube this loss can be reduced by inside coating of Teflon material in the pulse tube this experimentally observed by Ki et. al. [24]. They found that When Stycast 2850 FT material is used as the coating material, the no-load temperature they obtain from 38.4 K to 34.9 K and the cooling capacity is improved by 0.4 W.

B.A. Shah et. al. [25] carried out work which reports the performance the investigation on a basic pulse tube refrigerator. Air is used as a working substance for the experimental performance investigation, as helium is not readily available and also cost consideration.

Gawali et. al. [26] carried out an investigation on pulse tube refrigerator in which linear pulse tube refrigerator has been designed, fabricated and tested. The test results are obtained using air as a working fluid .the experimental results for varying orifice size, pulse rate and regenerator mesh size are discussed.

Matsubara et. al. [27] introduce two different types of thermal compressors instead of the mechanical compressor were introduced for the low frequency pulse tube system. Simplified work flow analysis has been developed to find out the feasibility of the thermal compressor system. Results indicate the cold thermal compressor operating between 300 K and 40 K could be applied to 4 K pulse tube cooler effectively.

S. Karthik et. al. [28] The development of a two-stage Pulse Tube Cryocooler (PTC) which produces a no-load temperature of 3 K and delivers a refrigeration power of 250 mW at 5 K is reported in this work. The system uses stainless steel meshes along with lead (Pb) granules and combinations of Pb, Er_3Ni and $HoCu_2$ in layered structures as the first and second stage regenerator materials respectively. With Helium as a working fluid, the pressure oscillations are generated using a 6 kW water-cooled Helium compressor along with an indigenous rotary valve. Different configurations of pulse tube systems have been experimentally studied, by both varying the dimensions of pulse tubes and regenerator as well as the second stage regenerator material composition. The pulse tube Cryocooler has been numerically analyzed by using both the isothermal model and the model based on solving the energy equations. The predicted refrigeration powers as well as the temperature profiles have been compared with the experimental results for specific pulse tube configurations.

T. Inada et. al. [29] presented the double inlet pulse tube refrigerator (DIPTR) has a mechanism which consist of an orifice valve, a bypass valve, and a reservoir tank at the hot end of the pulse tube. The mechanism bring about a phase angle between pressure and displacement of the working gas. Here to estimate the phase angle , instantaneous mass flow rates of the working gas through the orifice and bypass valves were measured by hot wire anemometer.

By changing regenerative material performance of the pulse tube cryocooler can be improve. Qui et. al. [30] used three layered regenerator which consist of woven wire screen, lead sphere and Er_3Ni. By using different wire mesh material and sizes. From experiment and calculation they conclude that 77.0% volume of Stainless steel wire mesh with mesh size 250, 18.4% volume of lead sphere and 4.6% volume of Er_3Ni regenerator is optimum to achieve the lowest temperature as 11.1 K for single stage PTR.

Inlet pressure of the pulse tube refrigerator is one of the most important character for cooling temperature. Fig. 2.15 shows variation for different temperature by changing pressure. cool down temperature will decrease by increasing the pressure of the compressor for DIPTR it was experimentally conclude by shah [31].

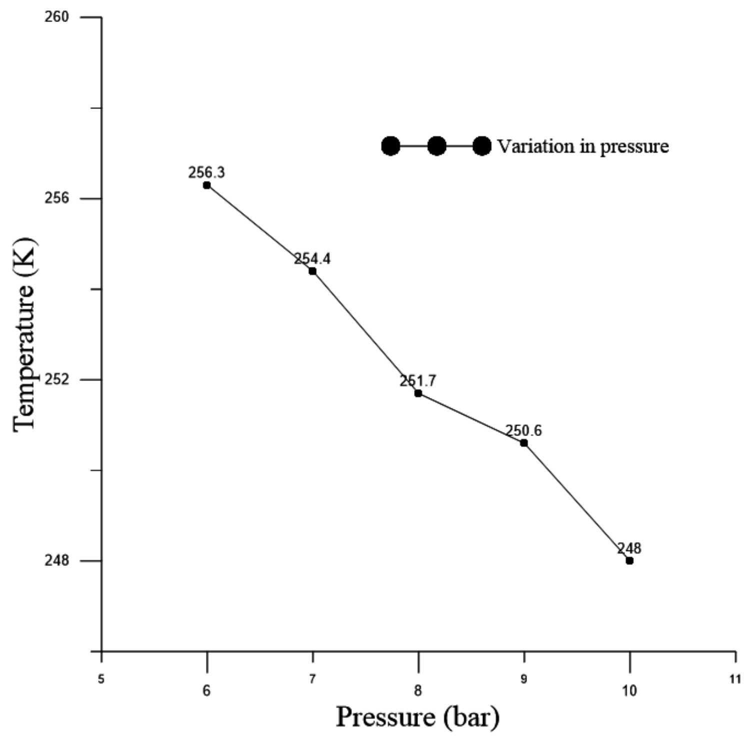

Figure 2.15: Pressure v/s cold end temperature [31]

2.5 CFD Work on PTR

Regenerator is the important part of the PTR. S.K. Rout et. al. [32] did numerical study with the help of CFD on single stage coaxial and inline inertance type pulse tube refrigerator. To find out the best regenerator material porosity, They set operating frequency for all case is 34 Hz, pulse tube diameter 5 mm and length is 125 mm for changing porosity of material

0.5 to 0.9. After analysis they conclude that porosity value of regenerator 0.6 as shown in Fig. 2.16 at which it gives a better cooling.

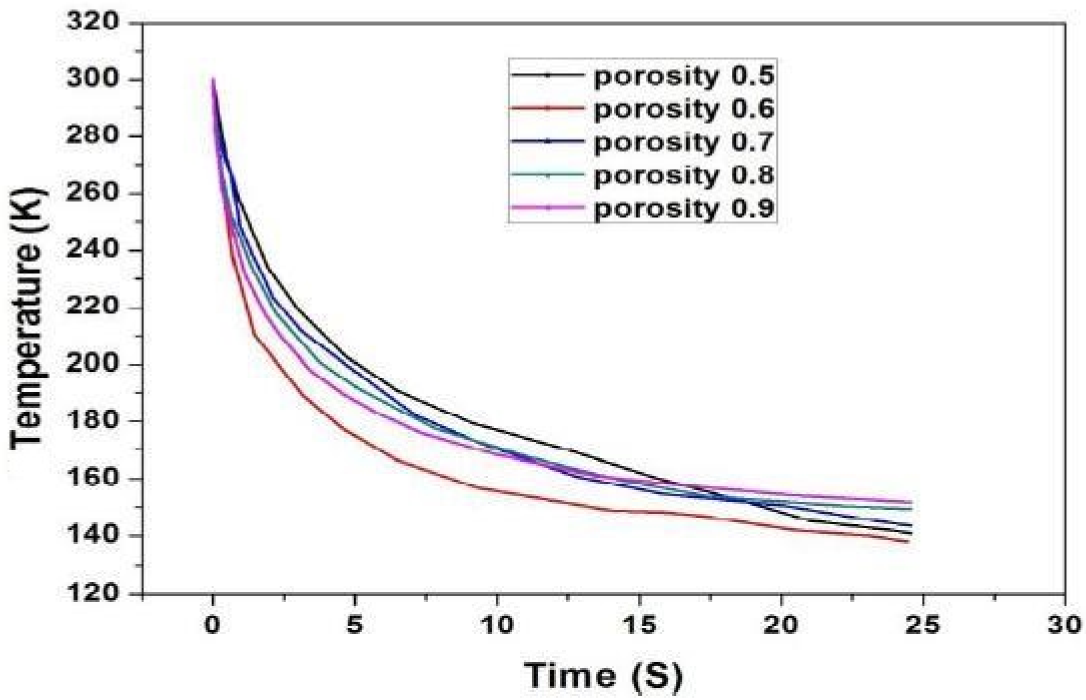

Figure 2.16: Cool down temperature v/s time for different porosity of regenerative material [32]

Phase difference in mass flow rate and pressure in Inertance tube type refrigerator can affect on refrigeration effect P. Mane et. al. [33] did numerical analysis of oscillation flow in CFD software of inline Inertance tube refrigerator they use helium as working medium and frequency 12 Hz. For regenerator stainless steel wire mesh and for heat exchangers copper wire meshes are used. By varying phase angle, they get lowest temperature 132 K at phase angle 40°. The mass flow rate is lagging the pressure wave.

By changing the valve opening conditions in DIPTR for different boundary conditions variation in refrigerating effect analyzed by Banjare et. al. [34] they did three different simulations are analyzed. First they assumed an adiabatic cold end heat exchanger; another assumed a known cooling load, and the last assumed a pre-specified temperature of cold end heat exchanger. After analysis they found that by opening double inlet valve 20% and orifice valve 30% offers a better potential for higher performance and efficiency compared with other values of valve openings. They also compare the experimental data and CFD simulation they get better cooling.

High capacity pulse tube refrigerator is a cryocoolers which can provide more than 250 W of cooling power at cryogenic temperatures. The most important characteristics of HCPTR when compared to other types of pulse tube refrigerators have a powerful pressure wave generator. Ghahremani et. al. [35] simulated and validate with the experimental data and reached 335 W cooling power at 80 K cold end temperature with a frequency of 50 Hz and COP of 0.05.

Jin et. al. [36] used optical fiber regenerator and compared with stainless steel wire mesh regenerator and by changing regenerator geometry, frequency, working pressure and input power were analyzed in CFD software. The results from the simulation show that optical fiber give better coefficient of performance (COP) as 0.136 at 80 K.

2.6 Regenerator Materials

The regenerator is one of the most important component in pulse tube refrigerator. Its function is to absorb heat from the incoming gas during the forward stroke of the compressor, and deliver that heat back to the gas during the return stroke. Ideally, regenerator with no pressure drop and a heat exchanger effectiveness of unity are desirable, in order to achieve the maximum enthalpy flow in the pulse tube. The performances of real regenerator are of course far from the ideal. The regenerator materials and geometries generally fall into three groups, based on the temperature range over which they are most commonly used. The first groups are the oven screen materials-such as stainless steel, bronze, and copper which are easy to weave into the screen geometry. These materials are used over the temperature range from 30K to 300K, where they provide the following advantages:

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

At temperature below 30 K screens lose their advantages and exhibit the following disadvantages:

- High void volume
- Low heat capacity

In the range between 10 K and 30 K lead and lead antimony spheres are used because of their higher heat capacity than any of the screen materials. In addition to the higher specific heat, spheres provide two advantages in this temperature range:

- Low void volume related to low porosity
- Low pressure drop reflecting the decrease in the fluid viscosity

A representation of regenerator materials used at different temperature range are shown in Fig. 2.17.

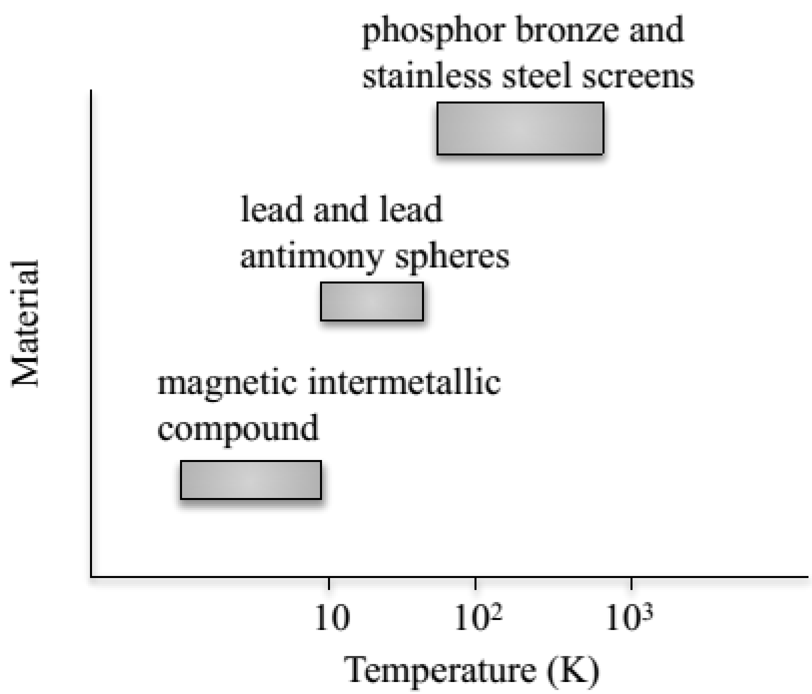

Figure 2.17: Temperature range for commonly used regenerative materials [38]

2.6.1 Porous media parameters for regenerator matrix [38]

The regenerator of a pulse tube refrigerator is a very critical component. The performance of any cryocooler greatly depends on regenerator material and its proper design. The regenerator is modeled as a porous media, for which some basic parameters like porosity, viscous resistance factor and inertial resistance factor are required as input parameters for CFD analysis. This section deals with the estimation of these basic parameters for regenerator porous matrix. The coefficients of porous media can be extracted from the experimental data in the form of pressure drop against velocity through the component. The oven wire mesh screen (Fig.) is the most commonly used regenerator material. Its advantages are that it provides a high heat transfer area with minimum pressure drop and it is readily available in mesh sizes from 50mesh (50x50 opening per square inch) to over 250mesh. It is also available in many different materials. Woven bronze screen regenerator are widely used in the first stage of all commercial regenerative cryogenic refrigerators to provide cooling down to 30K. Below 30K, the loss in specific heat of the commercially available materials, such as bronze and stainless steel, limits the effectiveness of screen packing.

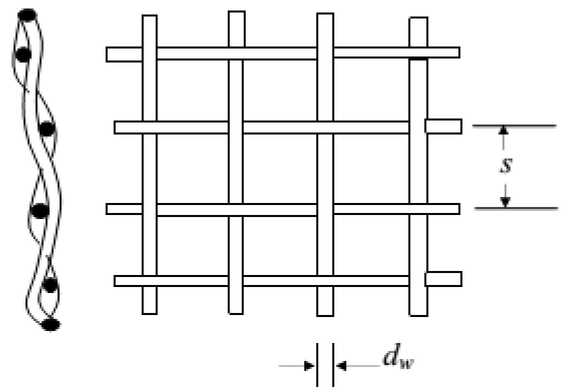

Figure 2.18: Woven wire mesh screen [38]

The geometrical parameters used in the description of screen regenerator are the porosity and area density. The porosity is defined as the ratio of the volume occupied by the fluid to the total volume. It could also be

Porosity $=\phi= \frac{\text{space void connected of volume total}}{\text{total volume of the matrix}}$

The area density is defined as the ratio of void surface area to the total volume of the matrix. It is expressed as:

Area density $= \sigma= \frac{\text{total surface area of connected void}}{\text{total volume of matrix}}$

From the porosity and area density, the important relationship for the hydraulic radius for a screen packing is given by

Hydraulic radius $= r_h= \frac{\phi}{\sigma}= \frac{\text{Fluid volume}}{\text{Heat transfer area}}= \frac{\text{Area}}{\text{Wetted perimeter}}$

Experimentally, the porosity and area density can be found from the dimensions and weight of the screens. The porosity is found by weighing the packed regenerator and subtracting their tare weight of the regenerator canister.

$\phi= 1-\frac{W_p}{\rho_m \cdot V_r}$

Where,

W_p is the weight of the packed matrix material,

ρ_m is the density of the packing (matrix),

V_r and is the regenerator volume.

The area density for one screen as shown in Fig. 2.18 is computed by calculating the circumferential heat transfer area of the wires and the total volume encompassed in one segment of screen mesh:

$$\sigma = \frac{A_s}{V_r} = \frac{\text{1/2 (Wire wetted perimeter) (Length of the opening) (4 sides)}}{\text{Volume encompassing the wire}}$$

$$\sigma = \frac{0.5\ (\pi \cdot d_w)(1/\mathrm{m})(4)}{(1/m)^2 t_s} = \frac{2\pi m d_w}{t_s}$$

Where,

d_w is the wire diameter,

t_s is the screen thickness, and

m is the mesh size.

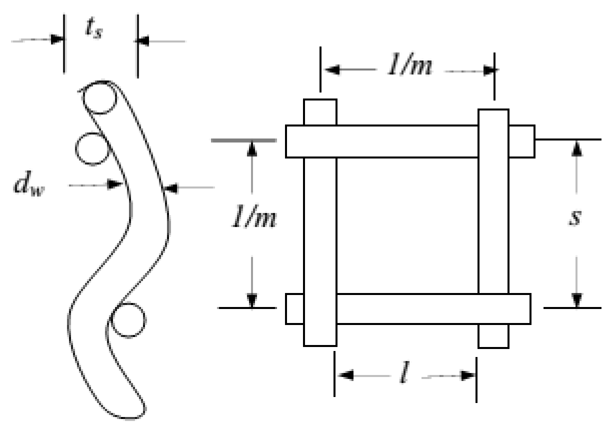

Figure 2.19: Geometry of woven screen [38]

From the area density, the total regenerator heat transfer area is given by,

A $= \sigma \times$Total volume of regenerator $\times$Total volume of the regenerator $= \left(\frac{2\pi m d_w}{t_s}\right)\left(\frac{\pi}{4}d_o^2\right)(t_s n)$

A $= d_w\left(\frac{\pi}{4}d_o^2\right)(nm)$

Where,

d_o is the outer diameter of the screens and

n is the total number of wire mesh screens used to pack the regenerator.

Analytically the porosity and area density are calculated by considering a small segment of screen with a transverse pitch, x_t (designating the transverse spacing/ factor between wires) and a lateral pitch,x_l(designating the longitudinal spacing/factor between wires). Referring to Fig. 2.19 the pitches are related to the mesh size and screen thickness by

$\frac{1}{m} = s = x_t d_w$and $t_s = 2x_l d_w$

The Fig. 2.19 is based on a perfect stacking of square mesh screens in which the weaving causes no inclination of the wires and the screen layers are not separated. These idealization lead to a matrix packing where the screen thickness, t_s,is equal to $2d_w$, and the porosity is given by,

$\phi = 1 - \frac{V_m}{V_r}$

Where,

V_m is volume occupied by the screen material.

Thus,

$\phi = 1 - \frac{2[(\pi/4)d_w^2](x_t d_w)}{(x_t d_w)^2(2d_w)} = 1 - \frac{\pi}{4x_t}$

Where,

$x_t = \frac{0.0254}{d_w m}$

where,

m is mesh per inch;

d_w is wire diameter of screen.

For a woven screen regenerator it is necessary to specify an additional analytical parameter, to define the ratio of the minimum free flow area to the frontal area. From the description of the screen geometry, shown in Fig. 2.19.

$\beta = \frac{\text{open area}}{\text{total area}} = \frac{(x_t d_w - d_w)^2}{(x_t d_w)^2} = \frac{(x_t - 1)^2}{(x_t)^2} = \left(\frac{l}{s}\right)^2$

The area density is given by

$\sigma = \frac{\pi}{x_t d_w}$

From the porosity expression and area density the hydraulic radius expression can be expressed as,

$r_h = \frac{\phi d_w}{4(1-\phi)}$

For a woven screen regenerator if the wire diameter and mesh per inch is given, porosity, area density and hydraulic radius can be analytically obtained from above equations.

2.7 Conclusion from the Literature Review

- For small cooling powered PTR, double inlet valve type pulse tube refrigerator can give more cooling effect than inertance tube pulse tube refrigerator.
- By replacing shape of the pulse tube is convergent taper instead of concentric gives better performance.
- Using hybrid PTRs lower cooling effects can be achieved but drawback is it has less COP.
- Using a ceramic material like $GdAl_3$ as a regenerator can helps to improve performance.

- There is a limitation to reach beyond the lambda point of the Helium as 4 K to overcome this problem ^{3}He should be used as a working gas.
- Inline arrangement is better than U type because of there is negligible friction losses in the connecting pipe.
- Cooling effect can be improved by increasing Porosity of the regenerative materials.
- In DIPTR 30% valve opening of double inlet and orifice valves gives better performance.
- Cool down temperature will decrease with increasing the input pressure of the PTR.

2.8 Objective of Present Work

Following are the objectives of the present work:

- To investigate optimum cycle time for different wire mesh size and materials for BPTR, OPTR & DIPTR with air as a working fluid.
- To investigate cool down characteristics of BPTR, OPTR, DIPTR.
- To compare effect of different wire mesh size and materials on Cool down characteristics of BPTR, OPTR and DIPTR.

Chapter 3

Experimental Work

3.1 Description of Experimental Setup

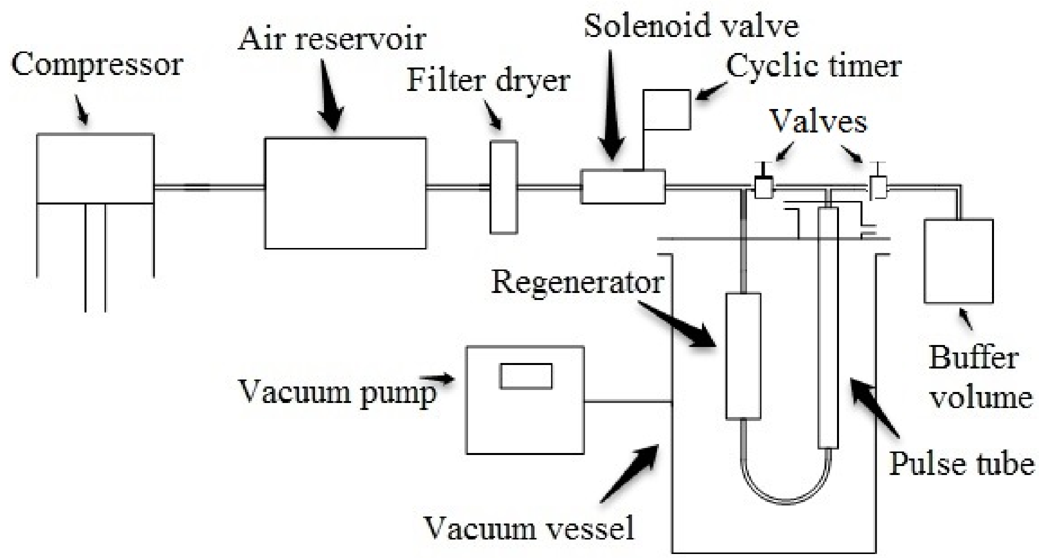

Figure 3.1: Schematic of the single stage double inlet pulse tube refrigerator

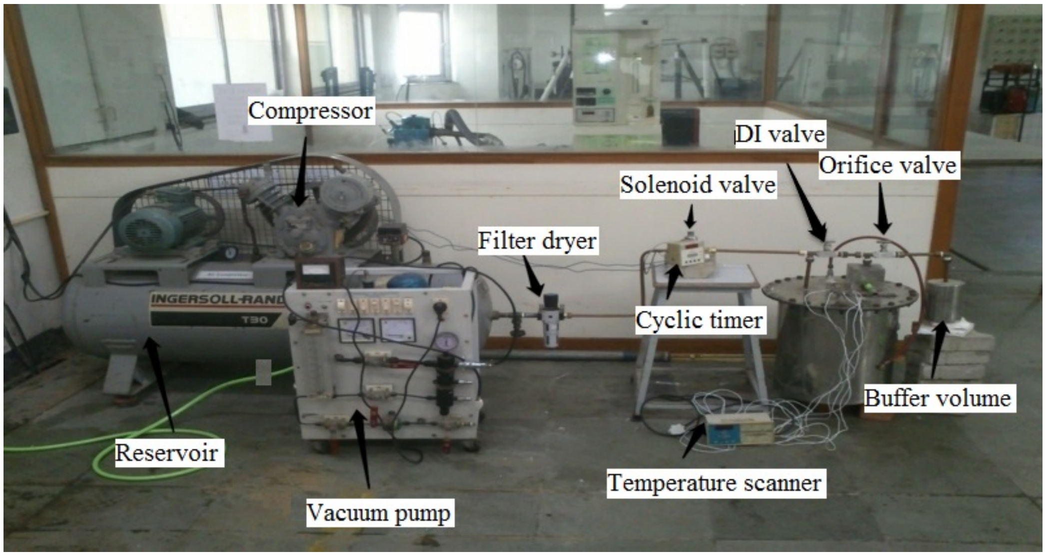

Figure 3.2: Experimental set up of pulse tube refrigerator

The schematic of the single stage pulse tube refrigerator is shown in Fig. 3.1. A 2.2 kW capacity commercial air compressor is used and the required pressure waves was achieved by 3/2 solenoid valve. The discharge pressure of the compressor can go up to 10 bar. A cyclic timer is used to vary the cycle time, so that the frequency of the pressure wave can be varied smoothly.Needle valves are used for bypass and orifice.

The regenerator is consist of about 1500 disk of 150, 200, 250, 300 wire mesh of stainless steel or 150 wire mesh phosphor bronze inside 16 mm o.d. and 1 mm wall thickness S.S seamless tube of length 200 mm. The pulse tube is made up of stainless steel tube of 14.9 mm o.d. and 0.9 mm wall thickness and 300 mm length. The water circulation was at the hot end through water jacket is used for heat removal. The pulse tube and regenerator assembly with platinum resistance temperature sensors (PT100) is kept inside the vacuum enclosure. The outlet from this unit forms the common inlet for both main and bypass lines. The buffer (reservoir) volume is almost 20 times the pulse tube. The vacuum vessel is connected to the rotary pump system. Rubber gasket with grease applied on is used to make the vacuum vessel leak proof that is top cover of vacuum vessel.

3.2 Components Description

3.2.1 Compressor

The main role of compressor in a pulse tube is to deliver high pressure working fluid to the regenerator and pulse tube. In this experiment, the Ingersoll rand make two stages single acting v-type reciprocating air compressor 3.3 is used.

Figure 3.3: Two stage v-type compressor with inter cooler

Table 3.1: Specification of compressor

Electric supply	3 phase
Capacity	2.2 kw
Speed	1415RPM
Frequency	50Hz
Range	2.7 bar to 12 bar

3.2.2 Filter drier

After compression of the air, air pressure will increase hence it produce some of the water particle, to remove water and oil particle air filter is used.

Figure 3.4: Air filter with regulator

1/2” standard AIRMAX make high flow separator is used.

Table 3.2: Specification of air filter

Model	JON - FRC
Body	Aluminum pressure die cast
Bowl guard	Steel Element: sinter bronze
Bowl size	25 micron
Weight	1.220 kg.

3.2.3 Solenoid valve system

The rotary valve is one of the critical components of pulse tube refrigerator. The rotary valve is shown in Fig. 3.5 . It is used to switch high and low pressure from a compressor to the pulse tube system. The high and low pressure of 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 aluminum block with predefined passages connecting the high and low pressures from the compressor. The rotational frequency of the synchronous motor is controlled using an cyclic timer. The rotary valve has been designed to produce pressure wave in the frequency range from 1 Hz to 3 Hz.

Figure 3.5: Solenoid valve

Fluid control valve are being designated as 2/2, 3/2, 3/3 or 5/2 type valve, in which first digit indicate number of port connection and second digit indicate number of position to which valve can be operated. So valve with 3 ports and 2 position is required depending on that 3/2 direct acting NC (normally closed) type valve is selected. Valve will remain closed initially and as current pass during on position it direct the high pressure air to the pulse tube and then during off position divert the low pressure air towards the atmosphere. The Rotex make 3/2 way direct acting solenoid valve (NC Type model no: 30125) has been selected.

3.2.4 Cyclic timer

Cyclic timer which is shown in Fig. 3.6 is used for controlling the valve opening and closing

Figure 3.6: Cyclic timer

. The cyclic timer is selected to set the valve time for minimum 0.1 sec ON/OFF. The valve opening and closing can be individually set by the timer.

3.2.5 Rotary vacuum pump module

Figure 3.7: Vacuum pump

Vacuum pumping system of HINDHIVAC PVT LTD, Bangalore has been used. The vacuum of 0.5 mbar (gauge) has been produced with this unit. The unit consists of rotary pump. Here pirani gauge is used for measuring the vacuum created. Vacuum helps to reduce conduction losses in the pulse tube refrigerators. HHV pump ED 6 as shown in Fig. 3.7. Specification of vacuum pump is shown in 3.3.

Vacuum pump down time is calculated for 0.1 mbar is 4.39 min form **??**.

Table 3.3: Specification of vacuum pump

Pumping speed	$6m^3/hr$
Pump rotational speed (no load)	1440rpm
Max nominal power rating	0.25 kw
Oil capacity	2 liter
Oil used	HHVP molecular distilled oil Grade MD-504

3.2.6 Needle valves

Figure 3.8: Needle valves

Needle valves 3.8 are orifice and bypass valve, which are used to control the mass flow rate, hence increases the performance of DIPTR.

3.2.7 Refrigeration system

The refrigeration system consists of regenerator, pulse tube and water-jacket.

- 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 regenerator 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 regenerator 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. Here 150, 200, 250, 300 of stainless steel & 150 phosphor bronze wire mesh is used as regenerator material near about 1500 wire mesh screen will stack inside the stainless steel regenerator housing.

Table 3.4: Dimension of pulse tube and regenerator

Dimension	Pulse Tube	Regenerator
Outer diameter	14.9 mm	18 mm
Inner diameter	13.1 mm	16 mm
Length	300 mm	200 mm
Internal volume	40.4 cm^3	40.2 cm^3

Table 3.5: The geometric factors of wire mesh screen [37]

Mesh size	Pitch	Wire dia.	Mesh distance	Dia. Pitch ratio	Opening area ratio	Porosity	Specific surface
No.	p (mm)	d_w(mm)	l (mm)	pr	β	ϕ	σ (mm)
150	0.169	0.061	0.108	0.361	0.408	0.699	16.41
200	0.127	0.05	0.077	0.394	0.368	0.668	21.72
250	0.101	0.04	0.061	0.396	0.365	0.665	27.3
300	0.084	0.04	0.044	0.476	0.274	0.586	32.52

- Pulse tube:

The pulse tube is the main component of the PTR. Pulse tube is nothing but a hollow tube, in which the expansion of the gas can takes place. 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 cold heat exchanger to the hot end heat exchanger. 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. Dimensional data has been given in the Table 3.4.

- Water jacket:

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.The hot compressed air is cooled by water supplied at atmospheric temperature. The hot length of 40 mm of pulse tube remains in the water jacket.

3.2.8 Vacuum vessel and buffer volume

The buffer volume can be viewed as a closed buffer reservoir of sufficient volume to allow for small pressure variations resulting from the oscillating mass flow. Buffer volume is connected to the copper tube through the hot end of pulse tube and is chosen to be 20 times greater to the pulse tube.

The regenerator and the pulse tube is enclosed in the vacuum vessel as shown in Fig. 3.9. With the help of vacuum pump pressure was maintained 0.5 mbar. This almost eliminates the infiltration of heat by convection. No part of cold end should be in contact with vacuum vessel. This helps avoid heat infiltration.

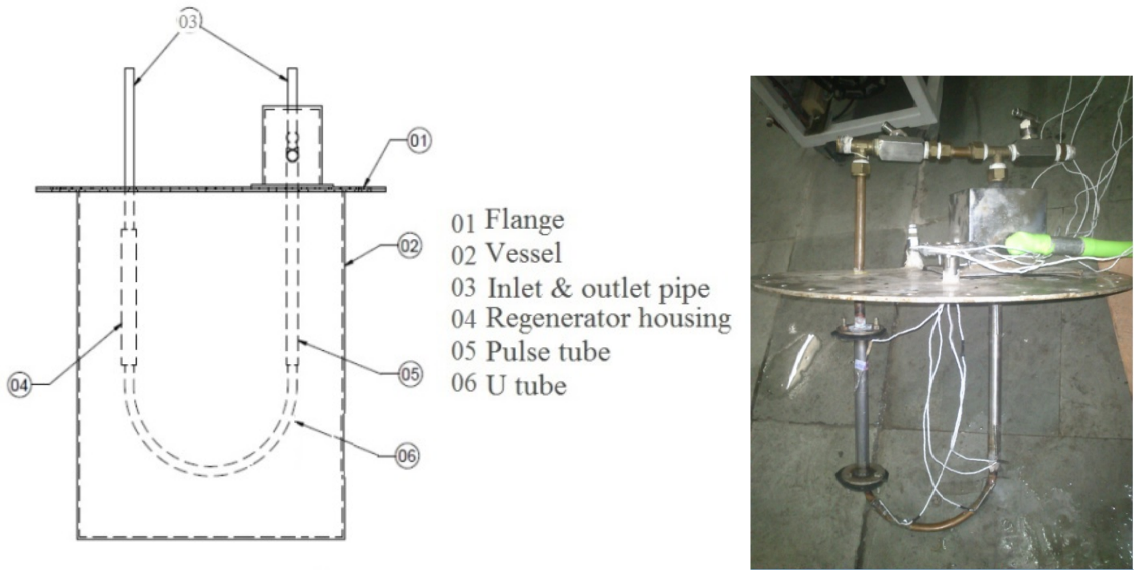

Figure 3.9: Vacuum vessel and refrigeration unit

3.2.9 Die for cutting wire mesh

The wire mesh was cut by preparing a die, Fig. 3.10. So, that it can fit exactly into the tube.different wire mesh material which has been used in the experimentation work is shown in Fig. 3.10.

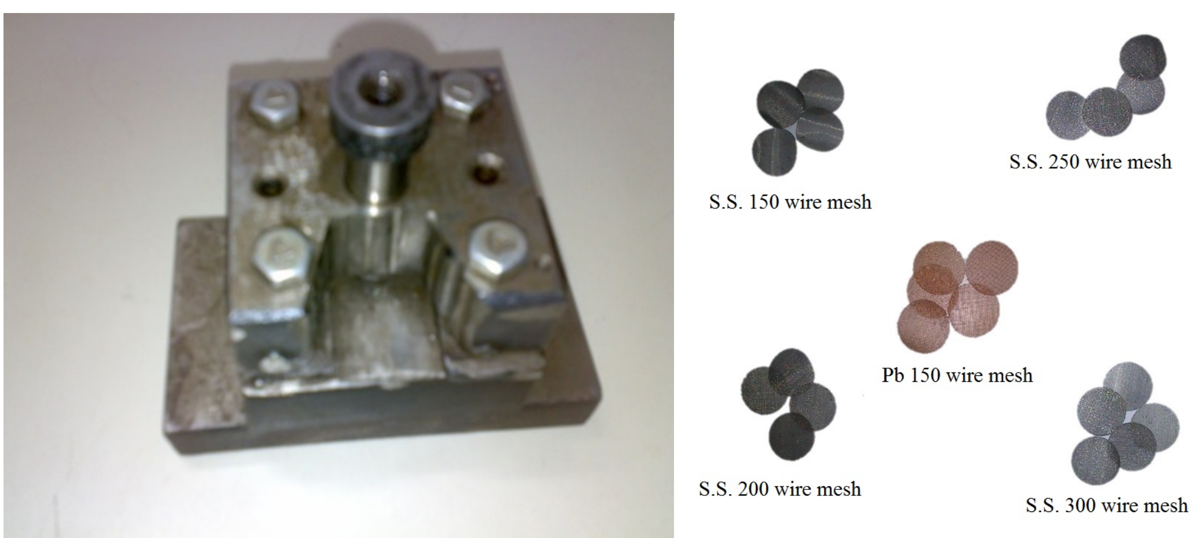

Figure 3.10: Die for cutting wire mesh

3.2.10 Leak test

First the system was charged with compressed air and checked for leak using soap solution. Leaks were found in the regenerator and vacuum vessel. By changing the gasket and using o-ring and gasket leaks were minimized in the allowable limits.

3.2.11 Loss analysis

The possible loss mechanisms that have been identified for DIPTR are pressure drop through the valve system and regenerator, conduction through the regenerator matrix, regenerator wall and pulse tube wall and radiation from ambient. The sample calculations are done using following formulas.

3.2.11.1 Loss due to regenerator ineffectiveness

The loss due to regenerator ineffectiveness is one of the major losses. The loss would vary with die rent mesh structures used in regenerator and also with the properties of mesh materials.

Loss due to regenerator ineffectiveness $= (1-\varepsilon)\, m_r \times C_p\,(T_h - T_c)$

3.2.11.2 Loss due to conduction through regenerator housing

It is the heat transferred through the regenerator housing between the hot end and the cold portion of the regenerator.

Loss due to conduction through regenerator housing$=K_{S.S.304} \times \pi \times D_{ro} \times t_r \times \left[(T_h - T_c)/L_T\right]$

3.2.11.3 Loss due to conduction through regenerator material matrix

It is heat transferred through the pulse tube material between the hot end and cold portion of the pulse tube.

Loss due to conduction through regenerator matrix material $= K_{mg} \times A_r \left[(T_h - T_c)/L_T\right]$

3.2.11.4 Loss due to conduction through pulse tube

It is heat transferred through the regenerator matrix material and gas between the hot end and cold portion of the regenerator.

Loss due to conduction through pulse tube $= K_{S.S.304} \times \pi \times D_{po} \times t_o \times \left[(T_h - T_c)/L_p\right]$

3.2.11.5 Loss due to radiation

It is heat transferred by radiation between the vacuum vessel and the regenerator material and between the vacuum vessel and pulse tube material.

Loss due to radiation $= \sigma \left[\varepsilon_{pv} \times A_p \times F_{pv} \left(T_v^4 - T_{pa}^4\right) + \varepsilon_{rv} \times A_r \times F_{rv} \times (T_v^4 - T_{ra}^4)\right]$
where,
σ = Stefan-Boltzmann constant = $5.67 \times 10^{-8}\ W/m^2K^4$
ε_{pv} = Emissivity factor for pulse tube and vacuum vessel $=[(1/\varepsilon_p) + (1/\varepsilon_v - 1)(A_p/A_v)]^{-1}$
$= [(1/\varepsilon_p) + (1/\varepsilon_v - 1)(D_p/D_v)]^{-1}$
ε_{rv}= Emissivity factor for regenerator and vacuum vessel $=[(1/\varepsilon_r) + (1/\varepsilon_v - 1)(A_r/A_v)]^{-1}$
$= [(1/\varepsilon_r) + (1/\varepsilon_v - 1)(D_r/D_v)]^{-1}$
F_{pv} =Shape factor for pulse tube and vacuum vessel of cylindrical geometry = 1
F_{rv}= Shape factor for regenerator and vacuum vessel of cylindrical geometry = 1
T_v =Temperature of vacuum vessel
T_{pa} =Average temperature of pulse tube
T_{ra} =Average temperature of regenerator

The other possible heat losses are pumping loss and shuttle loss, which are not being considered here, as that will occur at very low temperature only. The convection losses will be minimum as entire assembly has been kept inside a vacuum vessel pressure maintained at vessel around 0.5 mbar.

3.3 Procedure for Pulse Tube Refrigerator Operation

- Operation of pulse tube refrigerator

1. First start the vacuum module, maintain the desired pressure (0.5 mbar) in vacuum chamber in which pulse tube refrigerator has been placed.
2. Switch on the mains of air compressor.
3. As the desired pressure (10 bar) is reached pressure is reached in air compressor receiver, switch on the solenoid valve.
4. adjust the time according to required pulse rate.
5. Record the minimum temperature achieved.
6. Repeat the above procedure for various values of pulse rate and pressures.
7. Switch off the compressor then switch off the solenoid valve and then vacuum module respectively.

Chapter 4

Results and Discussion

As discussed in Chapter 2 & Chapter 3, experiments were carried out for (1) different regenerator material (2) different wire mesh size for BPTR, OPTR & DIPTR. Result observed during the experiments are presented in this Chapter.

4.1 Observation Tables and Graphs

4.1.1 Optimum cycle time for different wire mesh and materials

The experimental results were analyzed and the data has been summarized in graphical form for optimum cycle time for different regenerative material and wire mesh.

From the experimental data the cold end temperature has been plotted for different pulse rate such as 20, 21.42, 23, 25, 27.27, 30, 33.33, 37.5, 42.85, 50, 60,75 & 100 cycles/min, for S.S. 150, 200, 250, 300 wire mesh & phosphor bronze 150 wire mesh.

- Optimum cycle time for S.S. 150 wire mesh

Table 4.1: Optimum cycle time for BPTR, OPTR & DIPTR with S.S. 150 wire mesh

CYCLE TIME (Cyc./Min.)	VALVE TIMING (ON/OFF) (Sec)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
100	0.3	10.5	-0.1	-6.3
75	0.4	7.2	-2.2	-8.9
60	0.5	2.9	-5.7	-14.5
50	0.6	1.3	-7.5	**-16.4**
42.85	0.7	-0.3	**-8.7**	-15.5
37.5	0.8	-0.8	-8.3	-12.5
33.33	0.9	-1.5	-5.9	-8.5
30	1	**-5.7**	-5.7	-5.3
27.27	1.1	-4.8	-4	-4.2
25	1.2	-4	-2.6	-2.2

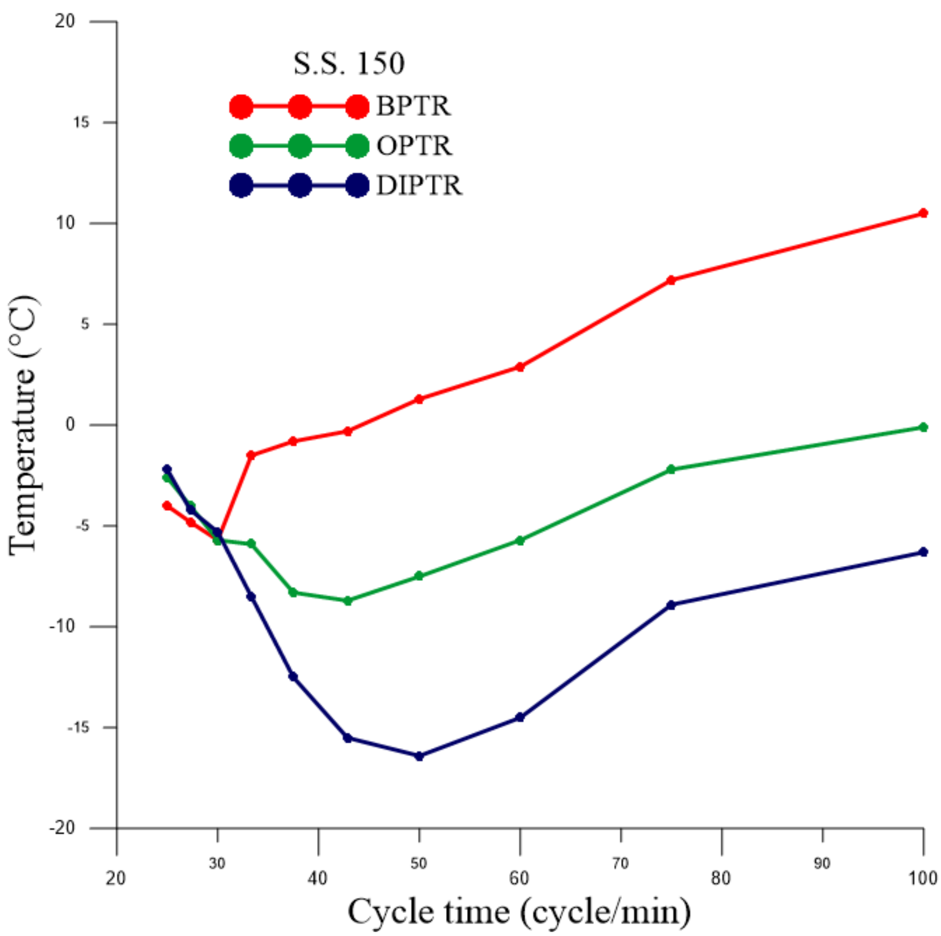

Figure 4.1: Optimum cycle time for S.S. 150 wire mesh for BPTR, OPTR & DIPTR

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 150 wire mesh and experiment has been carried out by considering different cycle time (frequency) 25, 27.27, 30, 33.33, 37.5, 42.85, 50, 60, 75 & 100 cycle/min. Comparison results for different cycle time are shown in Table 4.1 and based on that Graph 4.1 has been plotted.

Following observations has been taken for optimum cycle time

For BPTR cold end temperature = -5.7 °C for cycle time 30 cycle/min.

For OPTR cold end temperature = -8.7 °C for cycle time 42.85 cycle/min.

For DIPTR cold end temperature = -16.4 °C for cycle time 50 cycle/min.

- Optimum cycle time for S.S. 200 wire mesh

Table 4.2: Optimum cycle time for BPTR, OPTR & DIPTR with S.S. 200 wire mesh

CYCLE TIME (Cyc./Min.)	VALVE TIMING (ON/OFF) (Sec)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
60	0.5	11.4	1	-2.2
50	0.6	8.3	-1.6	-4.3
42.85	0.7	6.9	-2.6	-5.5
37.5	0.8	3.2	-3.1	**-6.3**
33.33	0.9	1.6	**-3.2**	-5.5
30	1	**1.4**	-2.8	-4.9
27.27	1.1	1.6	-2.2	-4.2
25	1.2	1.8	-1.8	-3.9
23	1.3	2.2	-1.2	-3.2
21.42	1.4	2.6	-1	-2.9
20	1.5	3	-0.6	-2.2

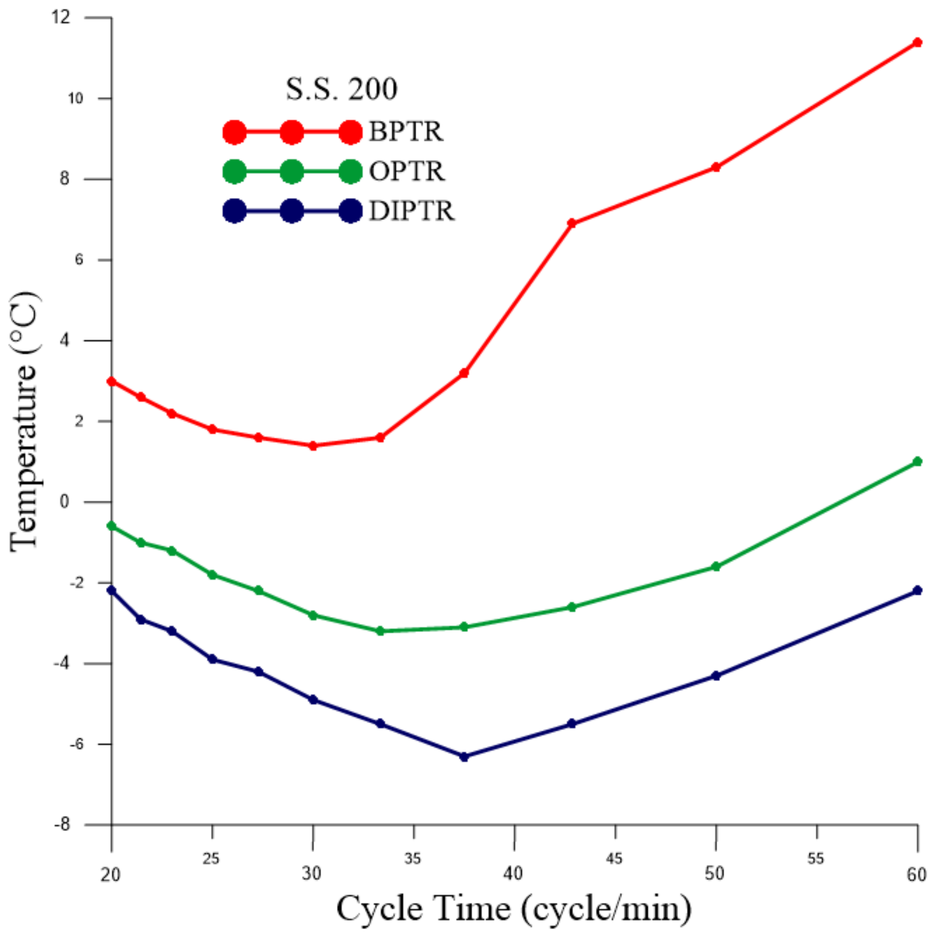

Figure 4.2: Optimum cycle time for S.S. 200 wire mesh for BPTR, OPTR & DIPTR

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 200 wire mesh and experiment has been carried out by considering different cycle time (frequency) 20, 21.42, 23, 25, 27.27, 30, 33.33, 37.5, 42.85, 50 & 60 cycle/min. Comparison results for different cycle time are shown in Table 4.2 and based on that Graph 4.2 has been plotted.

Following observations has been taken for optimum cycle time

For BPTR cold end temperature = 1.4 °C for cycle time 30 cycle/min.

For OPTR cold end temperature = -3.2 °C for cycle time 33.33 cycle/min.

For DIPTR cold end temperature = -6.3 °C for cycle time 37.5 cycle/min.

- Optimum cycle time for S.S. 250 wire mesh

Table 4.3: Optimum cycle time for BPTR, OPTR, DIPTR with S.S. 250 wire mesh

CYCLE TIME (Cyc./Min.)	VALVE TIMING (ON/OFF) (Sec)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
75	0.4	11.3	3.6	1.2
60	0.5	9	-3.2	-3.1
50	0.6	6.4	-3.6	-5.2
42.85	0.7	4.1	-4.8	-6
37.5	0.8	1.7	-5.2	-6
33.33	0.9	1.5	**-6.6**	**-8.5**
30	1	**0.5**	-5.4	-5.4
27.27	1.1	0.7	-4.2	-3.7
25	1.2	1.1	-3.4	-2.3
23	1.3	2.7	-0.7	-1.2

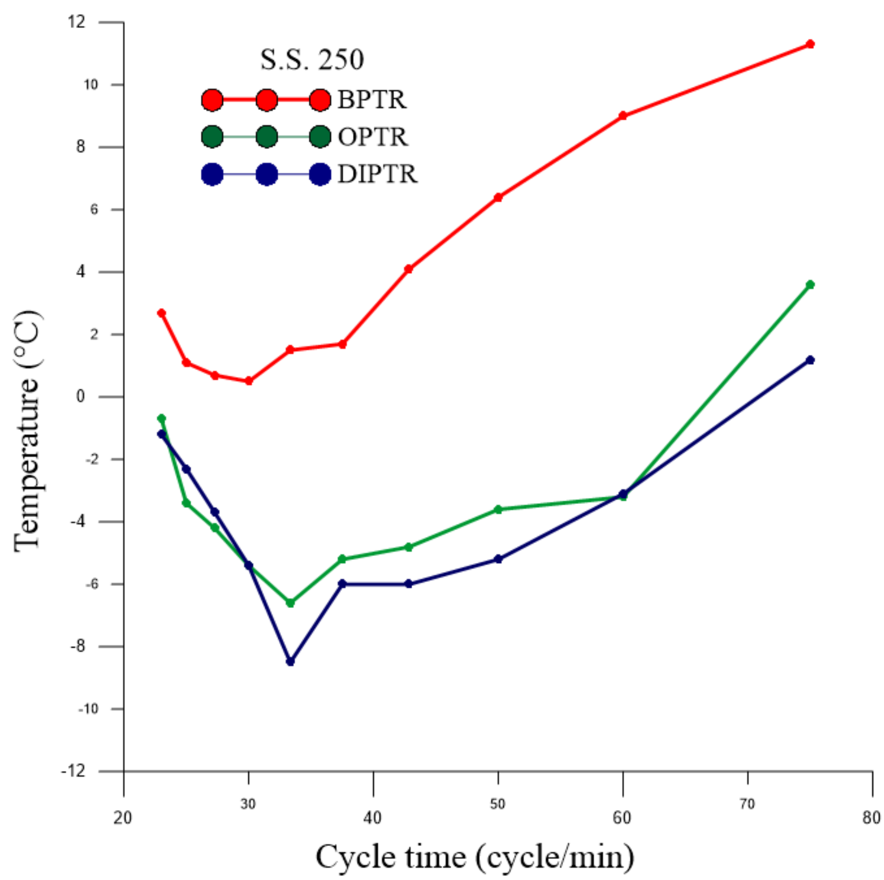

Figure 4.3: Optimum cycle time for S.S. 250 for BPTR, OPTR & DIPTR

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 250 wire mesh and experiment has been carried out by considering different cycle time (frequency) 23, 25, 27.27, 30, 33.33, 37.5, 42.85, 50, 60 & 75 cycle/min. Comparison results for different cycle time are shown in Table 4.3 and based on that Graph 4.3 has been plotted.

Following observations has been taken for optimum cycle time

For BPTR cold end temperature = 0.5 °C for cycle time 30 cycle/min.

For OPTR cold end temperature = -4 °C for cycle time 33.33 cycle/min.

For DIPTR cold end temperature = -7.6 °C for cycle time 33.33 cycle/min.

- Optimum cycle time for S.S. 300 wire mesh

Table 4.4: Optimum cycle time for BPTR, OPTR, DIPTR with S.S. 300 wire mesh

CYCLE TIME (Cyc./Min.)	VALVE TIMING (ON/OFF) (Sec)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
60	0.5	-0.4	-1.7	-4.4
50	0.6	-1.3	-2.1	-4.7
42.85	0.7	-1.8	-2.8	-5.5
37.5	0.8	-2.4	**-4.1**	-6.4
33.33	0.9	-2.9	-3.2	**-6.7**
30	1	-3.4	-3.1	-5.9
27.27	1.1	-3.6	-3	-5.5
25	1.2	**-3.8**	-2.8	-4.9
23	1.3	-3.3	-2.4	-4.3
21.42	1.4	-2.5	-1.8	-3.7
20	1.5	-2	-1.5	-3.5

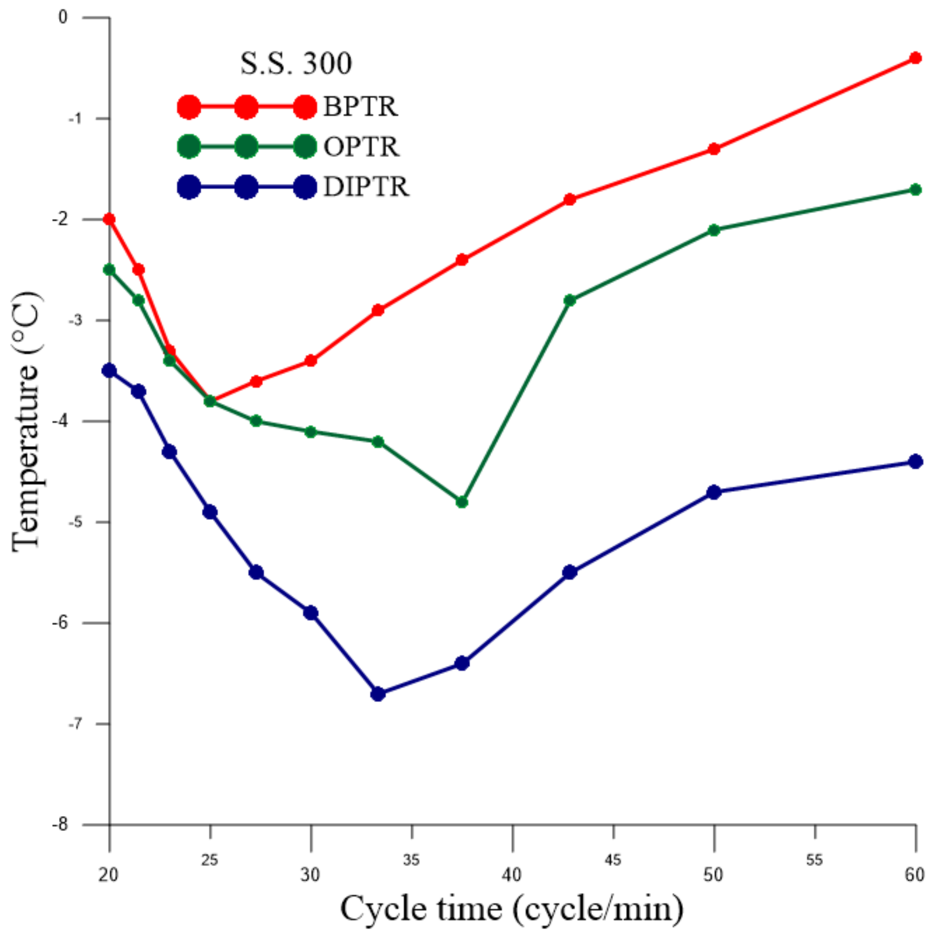

Figure 4.4: Optimum cycle time for S.S. 300 wire mesh for BPTR, OPTR, DIPTR

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 300 wire mesh and experiment has been carried out by considering different cycle time (frequency) 20, 21.42, 23, 25, 27.27, 30, 33.33, 37.5, 42.85, 50 & 60 cycle/min. Comparison results for different cycle time are shown in Table 4.4 and based on that Graph 4.4 has been plotted.

Following observations has been taken for optimum cycle time

For BPTR cold end temperature = -3.8 °C for cycle time 25 cycle/min.

For OPTR cold end temperature = -4.1 °C for cycle time 37.5 cycle/min.

For DIPTR cold end temperature = -6.7 °C for cycle time 33.33 cycle/min.

- Optimum cycle time for phosphor bronze 150 wire mesh

Table 4.5: Optimum cycle time for BPTR, OPTR, DIPTR with Phosphor bronze 150 wire mesh

CYCLE TIME (Cyc./Min.)	VALVE TIMING (ON/OFF) (Sec)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
60	0.5	4.2	-1.9	-2.6
50	0.6	3.8	-2.6	-3
42.85	0.7	2.1	-4	-4.8
37.5	0.8	0.9	**-5**	**-6.2**
33.33	0.9	-0.7	-4.8	-5.5
30	1	**-1**	-3.8	-4.7
27.27	1.1	-0.7	-3.2	-3.8
25	1.2	-0.5	-1.6	-3
23	1.3	1.2	-0.8	-2.2

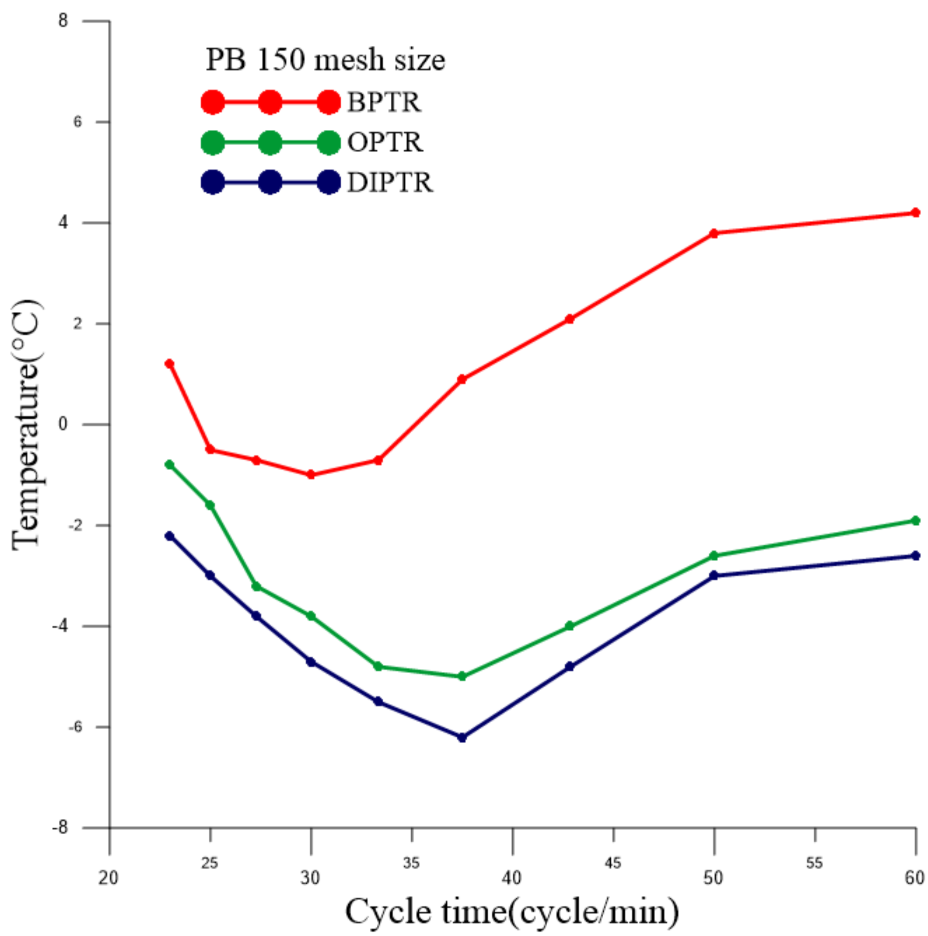

Figure 4.5: Optimum cycle time for Phosphor bronze 150 wire mesh for BPTR, OPTR, DIPTR

For BPTR, OPTR & DIPTR phosphor bronze used as a regenerative material having 150 wire mesh and experiment has been carried out by considering different cycle time (frequency) 20, 21.42, 23, 25, 27.27, 30, 33.33, 37.5, 42.85, 50 & 60 cycle/min. Comparison results for different cycle time are shown in Table 4.4 and based on that Graph 4.5 has been plotted.

Following observations has been taken for optimum cycle time

For BPTR cold end temperature = -4.5 °C for cycle time 30 cycle/min.

For OPTR cold end temperature = -7.5 °C for cycle time 37.5 cycle/min.

For DIPTR cold end temperature = -8.4 °C for cycle time 37.5 cycle/min.

4.1.2 Cool down characteristics of BPTR, OPTR, DIPTR with different regenerative materials

The experimental results were analyzed and the data has been summarized in graphical form for lowest cold end temperature by using different regenerative material and wire mesh for optimum cycle time.

From the experimental data the lowest cold end temperature has been plotted for time interval as 5 min for BPTR, OPTR, DIPTR by using regenerative material S.S. 150, 200, 250, 300 wire mesh & phosphor bronze 150 wire mesh for their optimum cycle time.

- Cool down characteristics of BPTR, OPTR, DIPTR with S.S. 150 wire mesh

Table 4.6: Cool down characteristics of BPTR, OPTR, DIPTR with S.S. 150 wire mesh

Time (Min.)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
0	24.9	24.9	24.9
5	11.4	12.2	12.9
10	5.9	9.8	-8.1
15	-2	6.2	-10.1
20	-3.9	-3.5	-14.3
25	-5.3	-6.3	-15.1
30	-5.7	-8.5	-15.8
35		-8.7	-16.1
40			-16.4

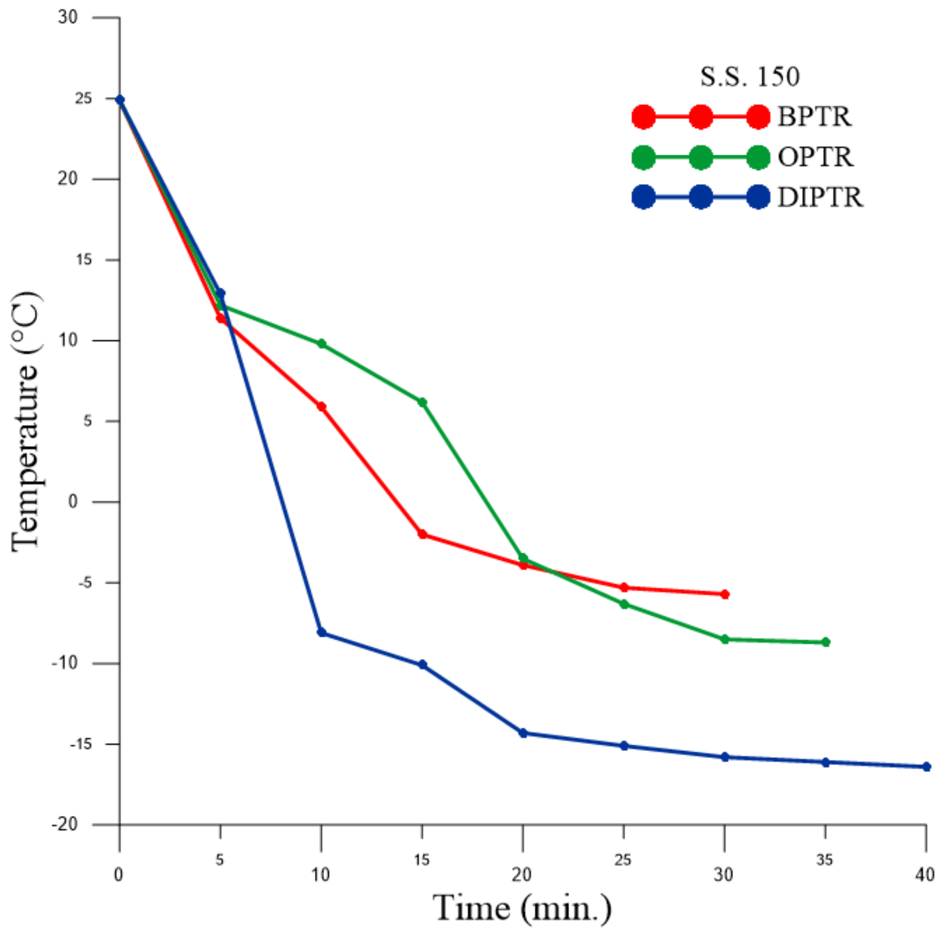

Figure 4.6: Cool down characteristics of BPTR, OPTR & DIPTR with 150 wire mesh

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 150 wire mesh and experiment has been carried out to achieve lowest cold end temperature by considering optimum cycle time. Comparison results for different geometric configurations are shown in Table 4.6 and based on that Graph 4.6 has been plotted.

Following observations has been taken for time to achieve lowest cold end temperature

For BPTR requires 30 min. to achieve cold end temperature = -4.5 °C.

For OPTR requires 35 min. to achieve cold end temperature = -8.7 °C.

For DIPTR requires 40 min. to achieve cold end temperature = -16.4 °C.

- Cool down characteristics of BPTR, OPTR, DIPTR with S.S. 200 wire mesh

Table 4.7: Cool down characteristics of BPTR, OPTR, DIPTR with S.S. 200 wire mesh

Time (Min.)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
0	26.3	25.1	24.2
5	12.8	6.5	5.1
10	7.3	2.9	0.2
15	3.1	0.4	-2.6
20	1.8	-1.4	-4
25	1.6	-2.4	-5.5
30	1.4	-2.8	-6.1
35		-3.2	-6.3

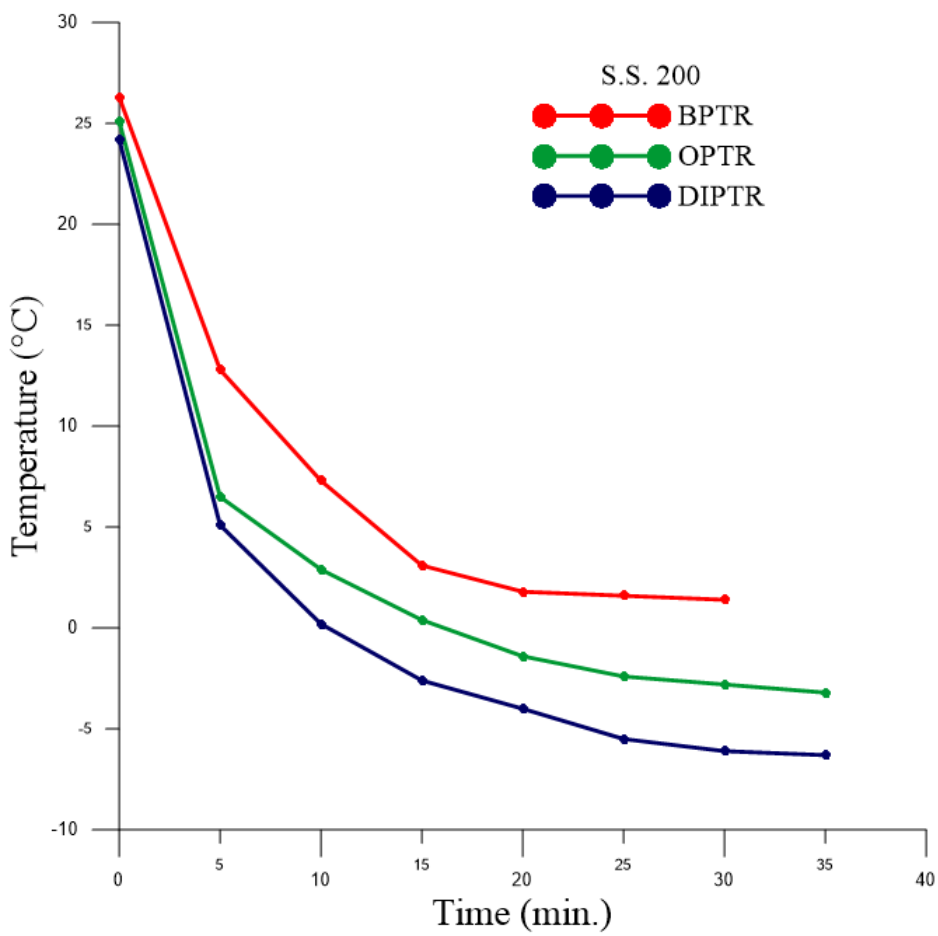

Figure 4.7: Cool down characteristics of BPTR, OPTR, DIPTR with 200 wire mesh

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 200 wire mesh and experiment has been carried out to achieve lowest cold end temperature by considering optimum cycle time. Comparison results for different geometric configurations are shown in Table 4.7 and based on that Graph 4.7 has been plotted.

Following observations has been taken for time to achieve lowest cold end temperature

For BPTR requires 30 min. to achieve cold end temperature = -1.4 °C.

For OPTR requires 35 min. to achieve cold end temperature = -3.2 °C.

For DIPTR requires 35 min. to achieve cold end temperature = -6.3 °C.

- Cool down characteristics of BPTR, OPTR & DIPTR with S.S. 250 wire mesh

Table 4.8: Cool down characteristics of BPTR, OPTR & DIPTR with S.S. 250 wire mesh

Time (Min.)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
0	25.7	24.3	24
5	9.8	4.5	4.4
10	7.6	2.4	-1.7
15	4.5	-0.5	-3.5
20	2.5	-2.3	-5.8
25	1.5	-3.4	-6.2
30	0.5	-4	-7.2
35			-7.6

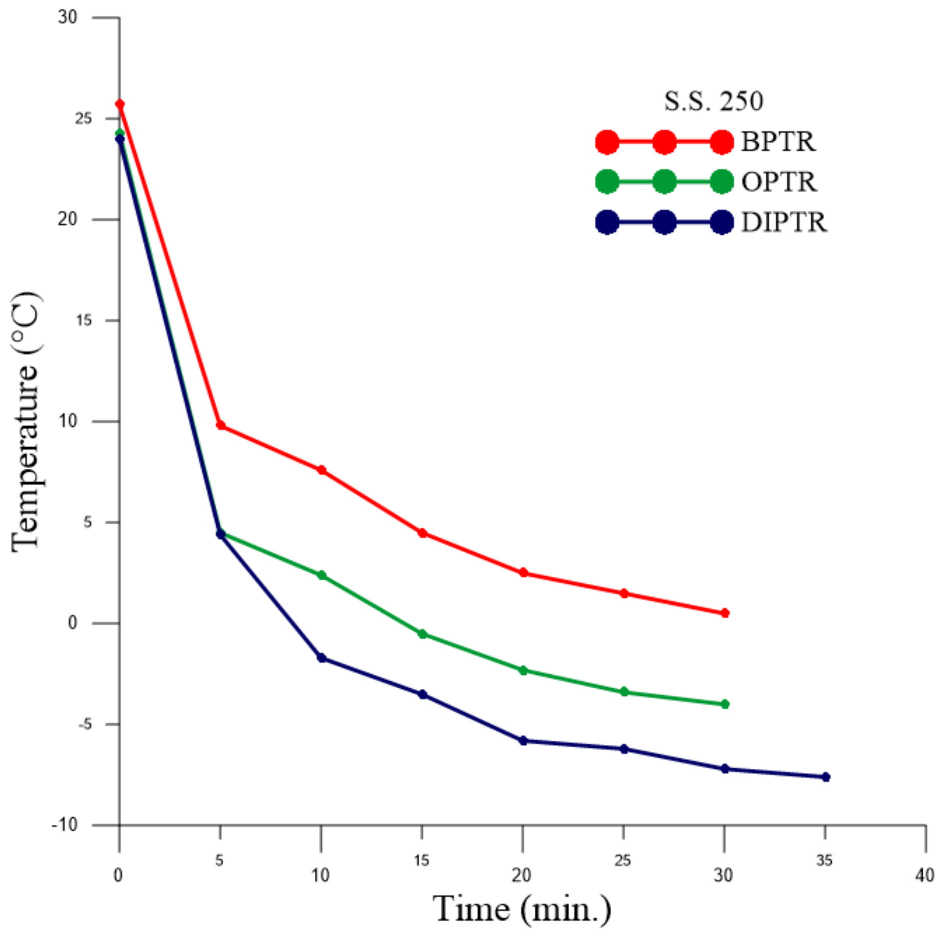

Figure 4.8: Cool down characteristics of BPTR, OPTR & DIPTR with 250 wire mesh

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 250 wire mesh and experiment has been carried out to achieve lowest cold end temperature by considering optimum cycle time. Comparison results for different geometric configurations are shown in Table 4.8 and based on that Graph 4.8 has been plotted.

Following observations has been taken for time to achieve lowest cold end temperature

For BPTR requires 30 min. to achieve cold end temperature = 0.5 °C.

For OPTR requires 30 min. to achieve cold end temperature = -4 °C.

For DIPTR requires 35 min. to achieve cold end temperature = -7.6 °C.

- Cool down characteristics of BPTR, OPTR & DIPTR with S.S. 300 wire mesh

Table 4.9: Cool down characteristics of BPTR, OPTR & DIPTR with S.S. 300 wire mesh

Time (Min.)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
0	22.4	22.6	23
5	11.2	10.3	8.6
10	6.4	6.8	5.9
15	2.2	2.5	4
20	-2.4	-0.3	1.9
25	-3.6	-2.1	-2.7
30	-3.8	-3.6	-5.9
35		-4.1	-6.4
40			-6.7

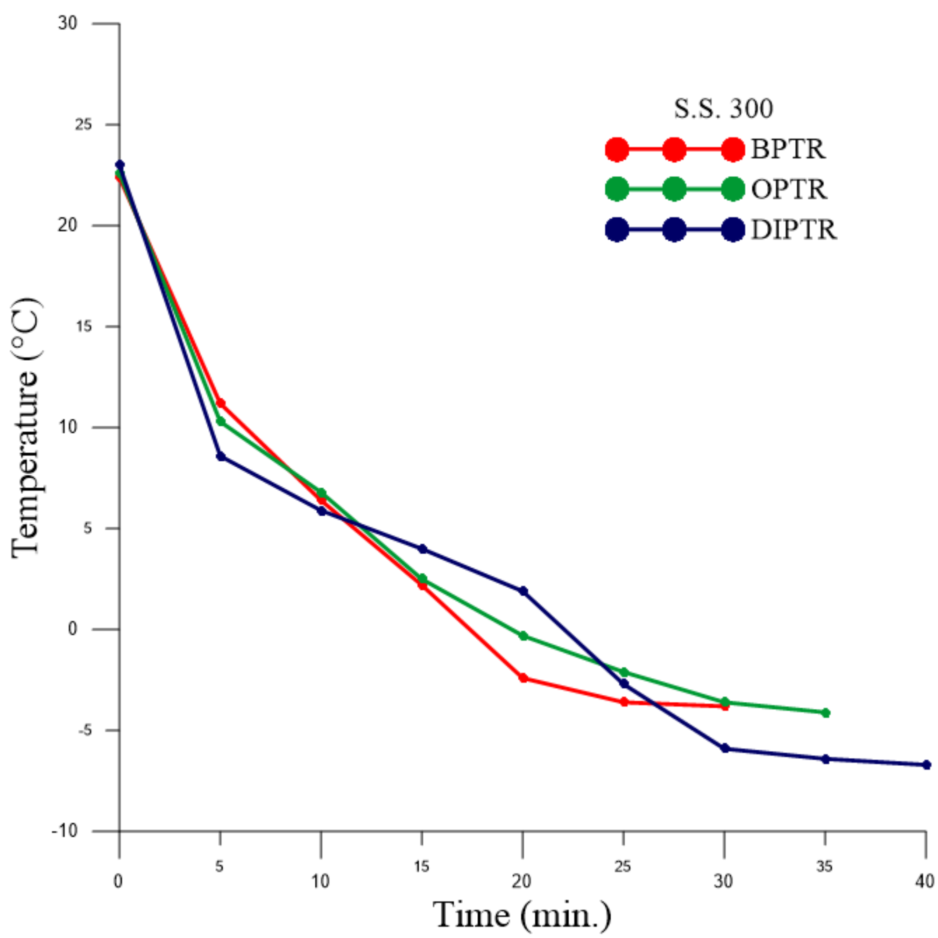

Figure 4.9: Cool down characteristics of BPTR, OPTR & DIPTR with S.S. 300 wire mesh

For BPTR, OPTR & DIPTR S.S. used as a regenerative material having 300 wire mesh and experiment has been carried out to achieve lowest cold end temperature by considering optimum cycle time. Comparison results for different geometric configurations are shown in Table 4.9 and based on that Graph 4.9 has been plotted.

Following observations has been taken for time to achieve lowest cold end temperature

For BPTR requires 30 min. to achieve cold end temperature = -3.8 °C.

For OPTR requires 35 min. to achieve cold end temperature = -4.1 °C.

For DIPTR requires 40 min. to achieve cold end temperature = -6.7 °C.

- Lowest temperature for BPTR, OPTR & DIPTR with Phosphor bronze 150 wire mesh

Table 4.10: Cool down characteristics of BPTR, OPTR & DIPTR with Phosphor bronze 150 wire mesh

Time (Min.)	BPTR (°C)	OPTR (°C)	DIPTR (°C)
0	23.5	23.8	23.3
5	6.3	7.8	5.1
10	2.6	3.2	-0.4
15	0.4	-1.1	-3.9
20	-1.5	-4	-5.5
25	-3.1	-5.4	-6.7
30	-4.5	-6.7	-7.6
35		-7.5	-8.4

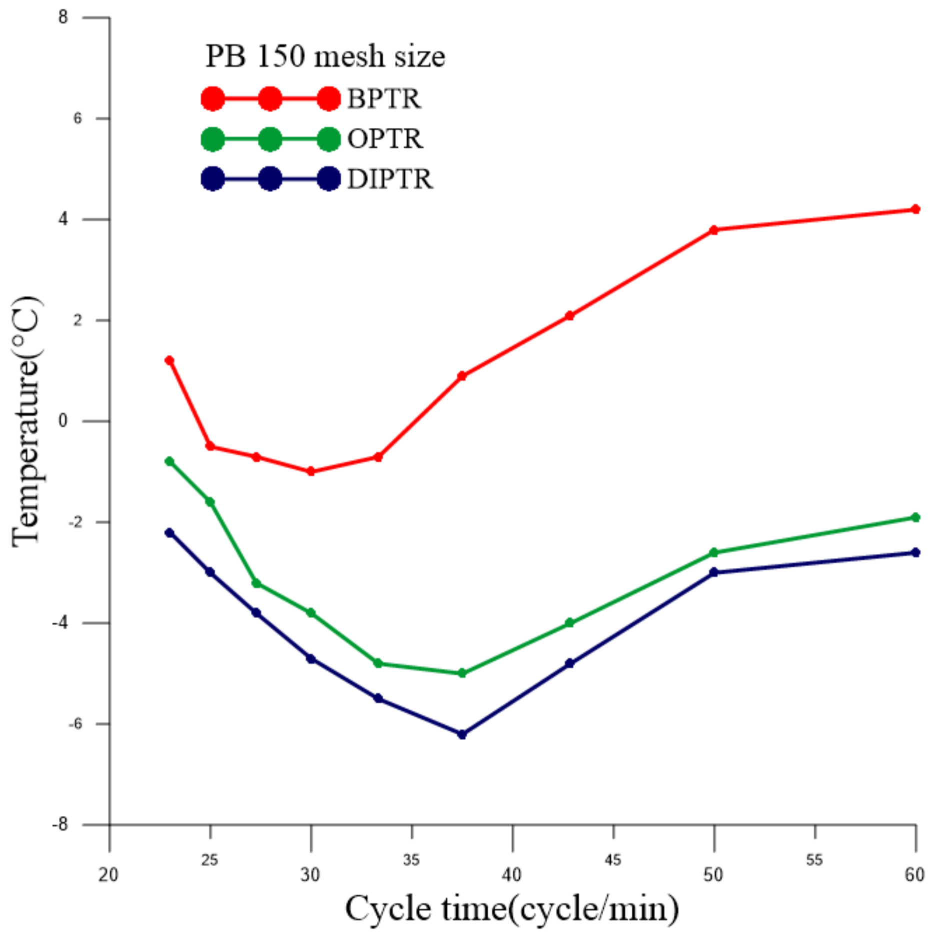

Figure 4.10: Cool down characteristics of BPTR, OPTR & DIPTR with Phosphor bronze 150 wire mesh

For BPTR, OPTR & DIPTR phosphor bronze used as a regenerative material having 150 wire mesh and experiment has been carried out to achieve lowest cold end temperature by considering optimum cycle time. Comparison results for different geometric configurations are shown in Table 4.10 and based on that Graph 4.10 has been plotted.

Following observations has been taken for time to achieve lowest cold end temperature

For BPTR requires 30 min. to achieve cold end temperature = -4.5 °C.

For OPTR requires 35 min. to achieve cold end temperature = -7.5 °C.

For DIPTR requires 35 min. to achieve cold end temperature = -8.4 °C.

4.1.3 Effect of different wire mesh on Cool down characteristics of BPTR, OPTR and DIPTR

The experimental results were analyzed and the data has been summarized in graphical form for lowest cold end temperature by comparing different material and different wire mesh size.

From the experimental data, comparison of lowest cold end temperature for S.S. 150 and phosphor bronze 150 and S.S. 150, 200, 250, 300 wire mesh size has been plotted for time interval as 5 min for BPTR, OPTR & DIPTR.

- Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of BPTR

Table 4.11: Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of BPTR

Time (Min.)	S.S. 150 (°C)	Pb 150 (°C)
0	24.9	24.9
5	11.4	11.3
10	5.9	7.6
15	-2	4.5
20	-3.9	2.3
25	-5.3	0.5
30	-5.7	-1

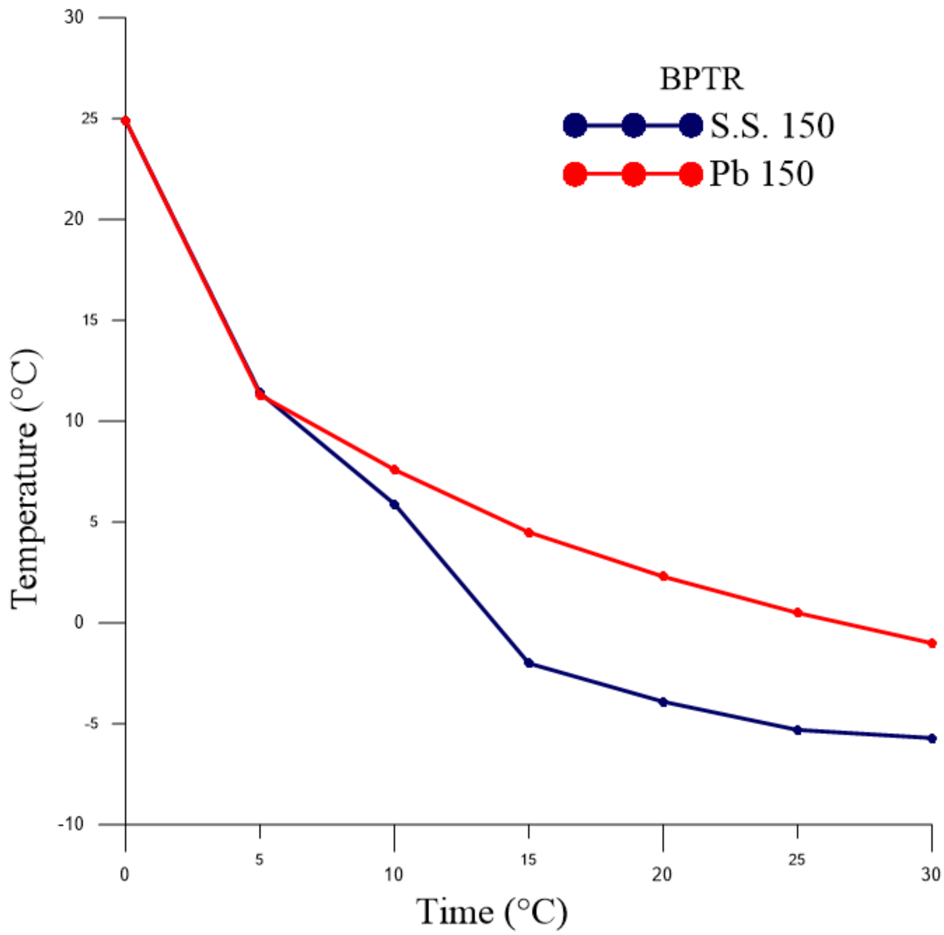

Figure 4.11: Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of BPTR

Table 4.11 shows the comparison of regenerative materials S.S. and phosphor bronze having 150 wire mesh for BPTR. Based on that Graph 4.11 has been plotted.

- Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of OPTR

Table 4.12: Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of OPTR

Time (Min.)	S.S. 150 (°C)	PB 150 (°C)
0	24.9	24.9
5	12.9	11.1
10	-8.1	3.2
15	-10.1	0.5
20	-14.3	-1.1
25	-15.1	-2.6
30	-15.8	-3.6
35	-16.1	-5.7
40	-16.4	-6.2

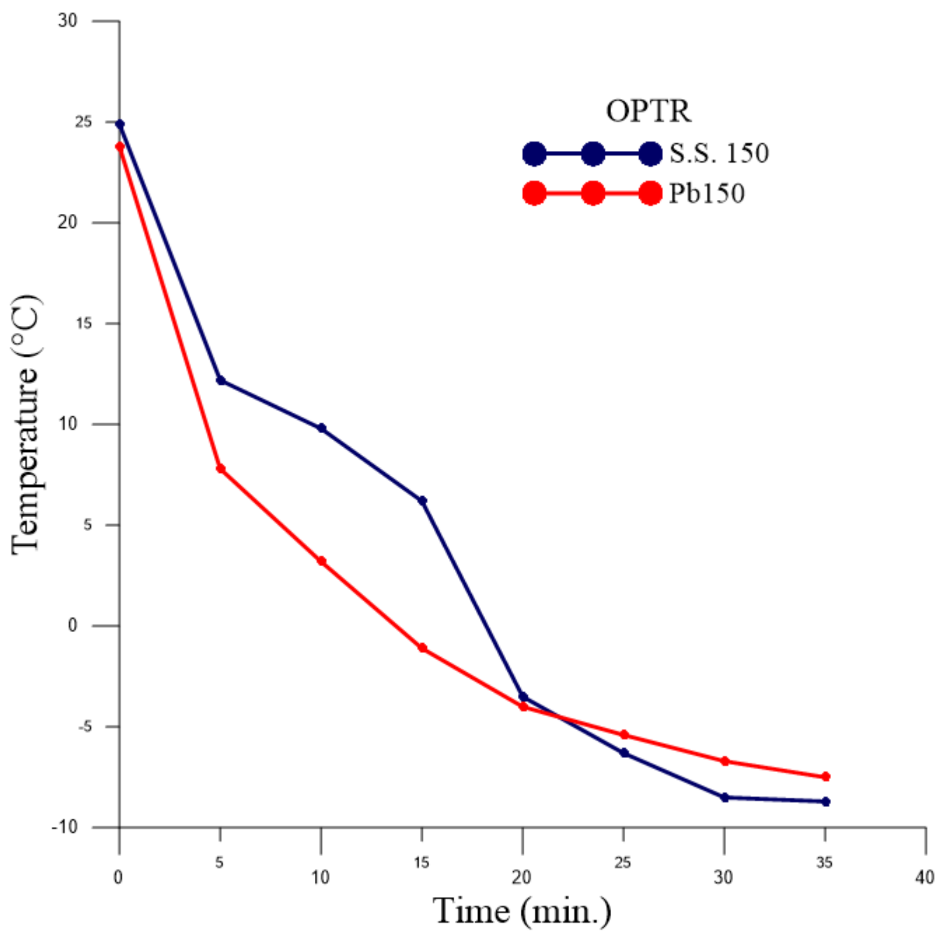

Figure 4.12: Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of OPTR

Table 4.12 shows the comparison of regenerative materials S.S. and phosphor bronze having 150 wire mesh for OPTR. Based on that Graph 4.12 has been plotted.

- Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of DIPTR

Table 4.13: Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of DIPTR

Time (Min.)	S.S. 150 (°C)	PB 150 (°C)
0	24.9	24.9
5	12.9	11.1
10	-8.1	3.2
15	-10.1	0.5
20	-14.3	-1.1
25	-15.1	-2.6
30	-15.8	-3.6
35	-16.1	-5.7
40	-16.4	-6.2

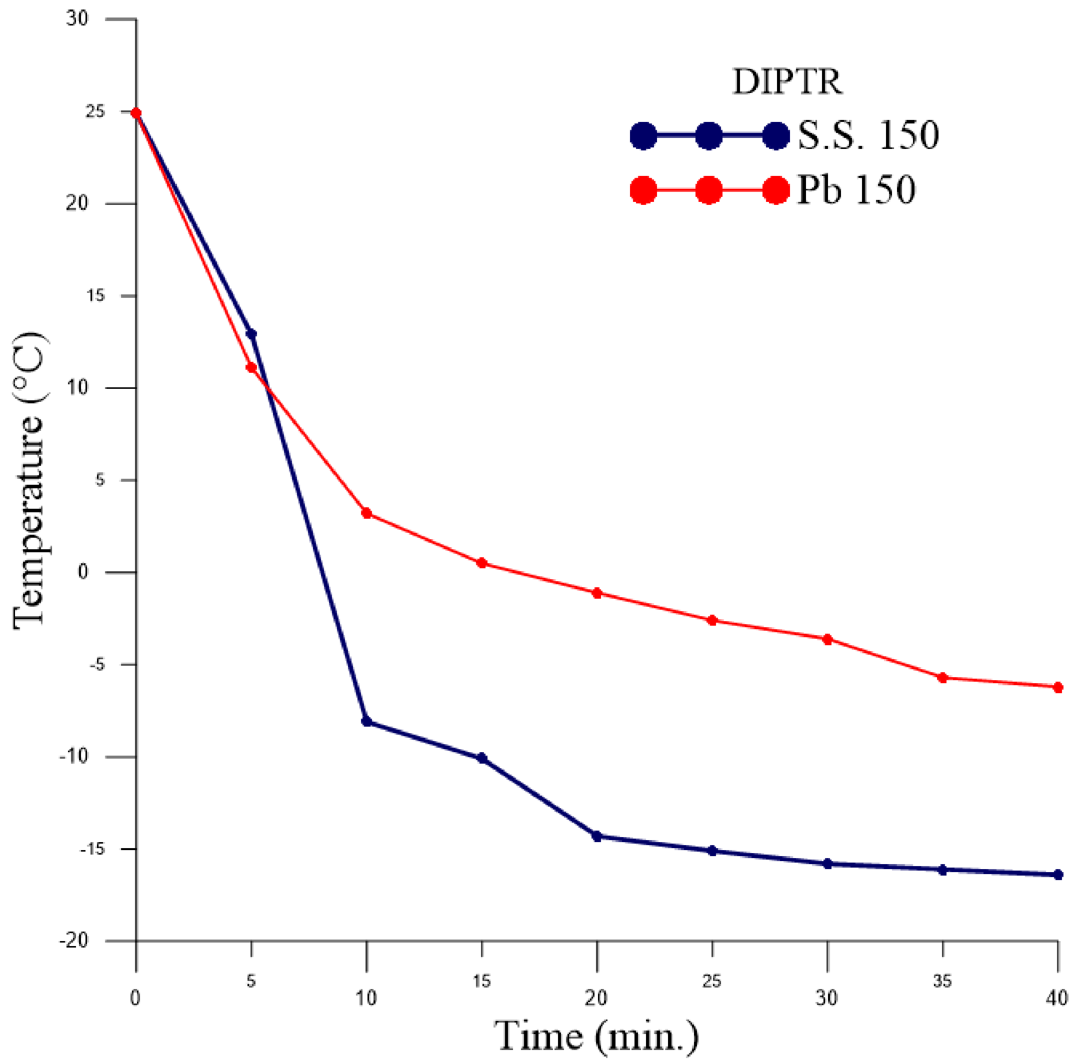

Figure 4.13: Effect of S.S. 150 & phosphor bronze 150 wire mesh on cool down characteristics of DIPTR

Table 4.13 shows the comparison of regenerative materials S.S. and phosphor bronze having 150 wire mesh for DIPTR. Based on that Graph 4.13 has been plotted.

- Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of BPTR

Table 4.14: Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of BPTR

Time (Min.)	S.S. 150 (°C)	S.S. 200 (°C)	S.S. 250 (°C)	S.S. 300 (°C)
0	24.9	26.3	25.7	22.4
5	11.4	12.8	9.8	11.2
10	5.9	7.3	7.6	6.4
15	-2	3.1	4.5	2.2
20	-3.9	1.8	2.5	-2.4
25	-5.3	1.6	1.5	-3.6
30	-5.7	1.4	0.5	-3.8

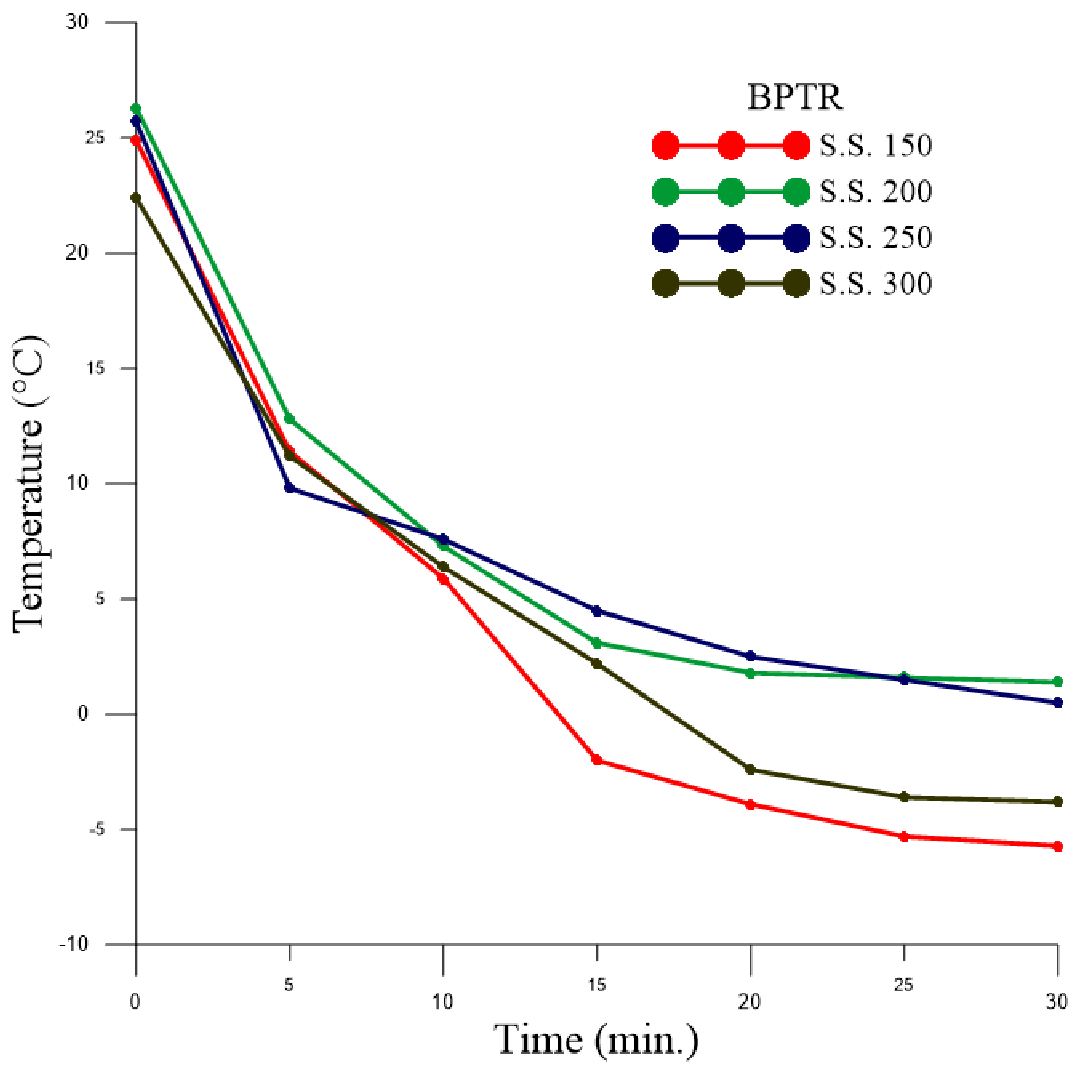

Figure 4.14: Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of BPTR

Table 4.14 shows the comparison of regenerative materials S.S. having 150, 200, 250 & 300 wire mesh for BPTR. Based on that Graph 4.14 has been plotted.

- Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of OPTR

Table 4.15: Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of OPTR

Time (Min.)	S.S. 150 (°C)	S.S. 200 (°C)	S.S. 250 (°C)
0	24.9	25.1	24.3
5	12.2	6.5	4.5
10	9.8	2.9	2.4
15	6.2	0.4	-0.5
20	-3.5	-1.4	-2.3
25	-6.3	-2.4	-3.4
30	-8.5	-2.8	-4
35	-8.7	-3.2	-4

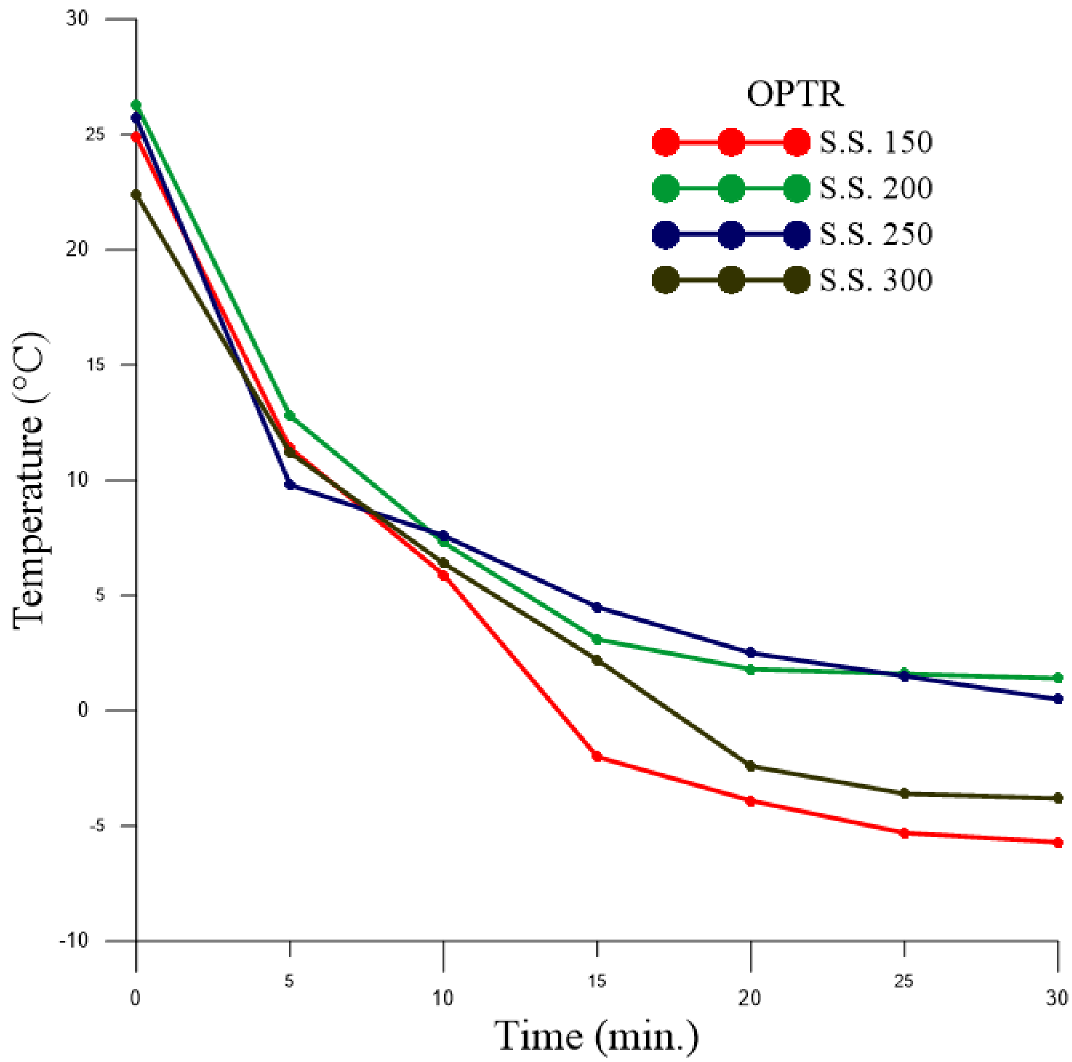

Figure 4.15: Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of OPTR

Table 4.15 shows the comparison of regenerative materials S.S. having 150, 200, 250 & 300 wire mesh for OPTR. Based on that Graph 4.15 has been plotted.

- Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of DIPTR

Table 4.16: Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of DIPTR

Time (Min.)	S.S. 150 (°C)	S.S. 200 (°C)	S.S. 250 (°C)
0	12.9	5.1	4.4
5	-8.1	0.2	-1.7
10	-10.1	-2.6	-3.5
15	-14.3	-4	-5.8
20	-15.1	-5.5	-6.2
25	-15.8	-6.1	-7.2
30	-16.1	-6.3	-7.6
35	-16.4	-6.3	-7.6

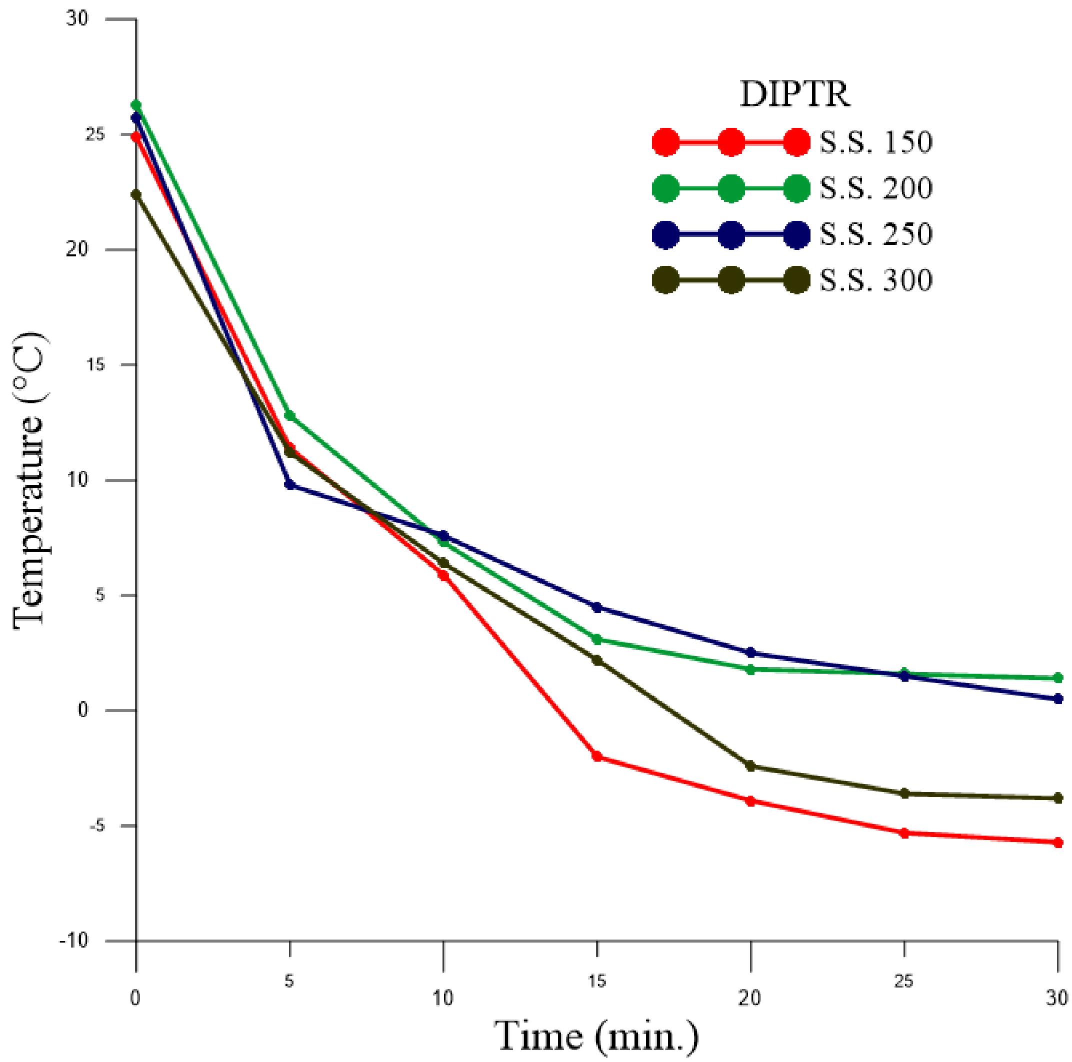

Figure 4.16: Effect of S.S. 150, 200, 250 & 300 wire mesh on cool down characteristics of DIPTR

Table 4.16 shows the comparison of regenerative materials S.S. having 150, 200, 250 & 300 wire mesh for DIPTR. Based on that Graph 4.16 has been plotted.

Chapter 5

Conclusions and Future Scope of Work

5.1 Conclusions

As experimental investigation was carried out for observing the effect of the regenerator material on performance of BPTR, OPTR & DIPTR. The series of tests were conducted using various regenerative material at different pulse rate with different wire mesh material for BPTR, OPTR & DIPTR.

After the comparison & analysis of the results some important conclusions are made.

1. For same regenerative material cycle time for lowest cold end temperature are different.

- For S.S. 150 wire mesh optimum cycle time for lowest cold end temperature for BPTR, OPTR & DIPTR are 30cycle/min., 42.85cycle/min. & 50 cycle/min. respectively.
- For S.S. 200 wire mesh optimum cycle time for lowest cold end temperature for BPTR, OPTR & DIPTR are 30 cycle/min., 33.33 cycle/min. & 37.5 cycle/min. respectively.
- For S.S. 250 wire mesh optimum cycle time for lowest cold end temperature for BPTR, OPTR & DIPTR are 30 cycle/min., 33.33 cycle/min. & 33.33 cycle/min. respectively.
- For S.S. 300 wire mesh optimum cycle time for lowest cold end temperature for BPTR, OPTR & DIPTR are 25 cycle/min., 37.5 cycle/min. & 33.33 cycle/min. respectively.
- For Phosphor bronze 150 wire mesh optimum cycle time for lowest cold end temperature for BPTR, OPTR & DIPTR are 30 cycle/min., 37.5 cycle/min. & 37.5 cycle/min. respectively.

2. It has been found that for same regenerative material OPTR gives better cooling than BPTR and DIPTR gives better cooling than OPTR.

- For S.S. 150 wire mesh lowest cold end temperature for BPTR, OPTR & DIPTR are -5.7°C, -8.7°C & -16.4 °C respectively.
- For S.S. 200 wire mesh lowest cold end temperature for BPTR, OPTR & DIPTR are 1.4°C, -3.2°C & -6.3 °C respectively.
- For S.S. 250 wire mesh lowest cold end temperature for BPTR, OPTR & DIPTR are 0.5°C, -4°C & -7.6 °C respectively.
- For S.S. 300 wire mesh lowest cold end temperature for BPTR, OPTR & DIPTR are -3.8°C, -4.1°C & -6.7 °C respectively.
- For Phosphor bronze 150 wire mesh optimum cycle time for lowest cold end temperature for BPTR, OPTR & DIPTR are -4.5°C, -7.5°C & -8.4 °C respectively.

3. It has been found that S.S. 150 wire mesh give better results compare to phosphor bronze 150 wire mesh.

- For BPTR lowest cold end temperature for S.S. and phosphor bronze wire mesh material are -5.7°C & -4.5 °C respectively.
- For OPTR lowest cold end temperature for S.S. and phosphor bronze wire mesh material are -8.7°C & -7.5 °C respectively.
- For DIPTR lowest cold end temperature for S.S. and phosphor bronze wire mesh material are -16.4°C & -8.4 °C respectively.

4. It has been found that with the increase in the wire mesh size lowest temperature achieved in BPTR, OPTR & DIPTR decreases due to increase in the pressure drop across the regenerator.

- For BPTR lowest cold end temperature for S.S. 150, 200, 250 & 300 wire mesh are -5.7°C, 1.4°C, 0.5°C & -3.8 °C respectively.
- For OPTR lowest cold end temperature for S.S. 150, 200, 250 & 300 wire mesh are -8.7°C, -3.2°C, -4°C & -4.1 °C respectively.
- For DIPTR lowest cold end temperature for S.S. 150, 200, 250 & 300 wire mesh are -16.4°C,-6.3°C, -7.6°C & -6.7 °C respectively.

5.2 Future Scope of Work

- By changing the different valve opening and closing time, lowest temperature at no load condition in BPTR, OPTR & DIPTR can be investigated.
- By using the hybrid regenerator (changing the ratio of the regenerative material) cool down temperature can be investigated.
- Experiment can also be carried out with different geometric configuration i.e. by varying the regenerator and pulse tube dimension and varying the hot end length.
- The experiments can be performed with helium or nitrogen as working fluid.

Bibliography

[1] Y.P. Banjare, "Theoretical and Experimental Studies on Pulse Tube Refrigerator", NIT, Rourkela, 2009.

[2] R. Radebaugh, "Development of the pulse tube refrigerator as an efficient and reliable cryocooler", Proc. Institution of Refrigeration, 1999-2000.

[3] W.E. Gifford and R.C. Longsworth, "Pulse tube refrigeration process", Advanced Cryogenic Engineering 3B, 1964; p69-79.

[4] S. Jacob, "Cryogenic technology", Center for Cryogenic Technology, Institute of Science, banglore, august 2007.

[5] R. Radebaugh, J. Zimmerman, D.R. Smith and B. Louie, "Comparison of three types of pulse tube refrigerators: new method for reaching 60 K", Advanced in Cryogenic Engineering 31, 1986; p779-789.

[6] E.I. Mikulin, A.A. Tarasov, and M.P. Shkrebyonock, "Low-temperature expansion pulse tubes", Advanced in Cryogenic Engineering 29, 1984; p629- 637.

[7] S. Zhu, P. Wu and Z. Chen, "Double inlet pulse tube refrigerators: an important improvement", Cryogenics 30, 1990; p514-520.

[8] P. Wu and S. Zhu, "Mechanism and numerical analysis of orifice pulse tube refrigerator with a valve less compressor", Proc. Int. Conf., Cryogenica and Refrigeration, 1989; p85-90.

[9] P. Neveu and B. Coret, "A simplified model for pulse tube refrigeration", Cryogenics 40, 2000; p191-201.

[10] Y. Kim, "Start up behavior of pulse tube refrigerators", Advances in Cryogenics 41, 2002; p1455-1462.

[11] M. Azadi, A. Jafarian and M. Timaji, "Analytical investigation of oscillating flow heat transfer in pulse tubes", Cryogenics 20, 2013; p483-491.

[12] J.Y. Hu, J. Ren, E.C. Luo, W. Dai, "Study on the inertance tube and double-inlet phase shifting modes in pulse tube refrigerators", Energy Conversion and Management 52, 2011; p1077–1085.

[13] Y.L. Ju and L. Wang, "On the numerical design of a new type of 4 k gm/pt hybrid refrigerators", Cryogenics 42, 2002; p533-542.

[14] K.P. Desai, "Phasor analysis of orifice pulse tube refrigerator", Eighteen Engineering Conference (ICEC18), Mumbai India, 2000.

[15] A.I. Razani, T. Roberts, B. Flake, "A thermodynamic model based on exergy flow for analysis and optimization of pulse tube refrigerators", Cryogenics 47, 2007; p166–173.

[16] X. Yong, J.N. Chung, "Size effect on miniature stirling cycle cryocooler", Cryogenics 45, 2005; p537-545.

[17] X.N. Richardson, "Development of a practical pulse tube refrigerator: co-axial designs and the influence of viscosity". Cryogenics 28, 1988; p516-520.

[18] S. Zhu, M. Nogawa, T. Inoue, "Numerical simulation of a step-piston type series two-stage pulse tube refrigerator", Cryogenics 47, 2007; p483-489.

[19] T. Ki, S. Jeong, "Step-by-step design methodology for efficient Stirling-type pulse tube refrigerator", International Journal of Refrigeration 35, 2012; p1166-1175.

[20] Y. He, J. Huang, C. Zhao and Y. Liu, "First and second law analysis of pulse tube refrigerator", Applied Thermal Engineering 26, 2006, p2301-2307.

[21] L.M.Qiu, T.Numazawa, G.Thummers, "Performance improvement of pulse tube cooler below 4 K by use of $GdAlO_3$ regenerator material", Cryogenics 52, 2001; p575-579.

[22] M.Y. Xu, A.T.A.M. de Waele, and Y.L. Ju, "A pulse tube refrigeration below 2 K", Cryogenics 39; p865-869.

[23] K. Wang, Q.R. Zheng, C. Zhang, W.S. Lin, X.S. Lu and A.Z. Gu, "The experimental investigation of a pulse tube refrigerator with a ‘L’ type pulse tube and two orifice valves", Cryogenics 46, 2006; p643-647.

[24] T. Ki, S. Jeong, "Design and analysis of compact work recovery phase shifter for pulse tube refrigerator", Cryogenics 52, 2012; p105-110.

[25] B.A. Shah, "Investigation on pulse tube refrigeration", International Conference on Advances in Mechanical Engineering, 2006.

[26] B.S. Gawali, "Experimental investigation on pulse tube refrigerator", Eighteen Engineering Conference (ICEC18), Mumbai, India, 2000.

[27] S.Y. Matsubara, "Feasibility study of applying thermal compressor to 4 K pulse tube cooler", Eighteen Engineering Conference (ICEC18), Mumbai, India, 2000.

[28] G.S. Karthik, "Effects of reservoir volume on performance of pulse tube cooler", International Journal of Refrigeration 30, March 2007; p11-18.

[29] T. Inada, S. Nishio, Y. Ohtani, T. Kuriyama, "Experimental investigation on the role of orifice and bypass valves in double inlet pulse tube refrigerator", Advances in Cryogenics 41, 2002; p1479-1486.

[30] L.M. Qiu, Y.L. He, Z.H. Gan, X.B. Zhang, G.B. Chen, "Regenerator performance improvement of a single-stage pulse tube cooler reached 11.1 K", Cryogenic 47, 2007; p49-55.

[31] H. shah, "Design, development and performance investing of double inlet pulse tube refrigerator", M.tech thesis, 2007.

[32] S.K. Rout, A.K. Gupta, B.K. Choudhury, R.K. Sahoo , S.K. Sarangi, "Influence of porosity on the performance of a pulse tube refrigerator: a CFD study", Procedia Engineering, vol. 51, 2012; p609-616.

[33] P. Mane, A. Dasare, G. Deshmukh, P. Bhuyar, K. Deshmukh, A. Barve, "Numerical analysis of pulse tube cryocoolers", International Journal of Innovative Research in Science, Engineering and Technology, vol. 2, 2013.

[34] Y.P. Banjare, R.K. Sahoo, S.K. Sarangi, "CFD simulation of a Gifford–McMahon type pulse tube refrigerator", International Journal of Thermal Sciences, vol. 48, 2009; p2280-2287.

[35] A. R. Ghahremani, M.H. Saidi , R. Jahanbakhshi, F. Roshanghalb, "Performance analysis and optimization of high capacity pulse tube refrigerator", Cryogenics, vol. 51, 2011; p173-179.

[36] T. Jin, J.L. Huang, K. Tang, M.X. Wu, "Performance analysis of a micro-scale pulse tube cryocooler based on optical fiber regenerator", Cryogenic, vol. 55-56, 2013; p30-34.

[37] H. Miyabe, S. Takahashi and K. Hamaguchi, "An approach to the design of Stirling engine regenerator matrix using packs of wire gauzes", Proc. 17^{th} IECEC, vol. 1, 1982; p1839–1844.

[38] R. Ackerman , 1st ed. “cryogenic heat exchangers”, Plenum press.

Appendix - A
Loss Analysis

1. Loss Due To Regenerator Ineffectiveness

   $= (1 - \varepsilon)\, m_r \times C_p\,(T_h - T_c)$

   $= (1 - 0.9975) \times 6.31 \times 10^{-3} \times 1.005 \times 10^{3} \times (301 - 256.6)$

   $= 0.067$ W

2. Loss Due To Conduction through Regenerator Housing

   $= K_{s.s.304} \times \pi \times D_{ro} \times t_r \times [(T_h - T_c)\,/L_t]$

   $= 19 \times \pi \times 19.1 \times 1 \times 10^{-6} \times [(301 - 256.6)\,/0.200]$

   $= 0.25$ W

3. Loss Due To Conduction through Regenerator Material Matrix

   $= K_{mg} \times A_r\,[(T_h - T_c)\,/L_t]$

   $= K_{mg} \times A_r[T_h - Tc/L_r]$

   $Now,$

   $K_{mg} = K_g[(1 - ev)/\,(1 + ev)]$

   $ev = 0.699$

   $K_{mg} = 0.133W/mK$

   $= 0.133 \times (\pi/4) \times (19.2 \times 10^{-3})^2 \times [(301 - 256.6)/0.2]$

   $= 0.0078$ W

4. Loss Due To Conduction through Pulse Tube

   $= K_{s.s.304} \times \pi \times D_{po} \times t_o \times [(T_h - T_c)\,/L_p]$

   $= 19 \times \pi \times 14.9 \times 10^{-3} \times 10^{-3}[(301 - 256.6)/0.2]$

   $= 0.125$ W

5. Loss Due To Radiation

   $= \sigma\left[\varepsilon_{pv} \times A_p \times F_{pv}\left(T_v^4 - T_{pa}^4\right) + \varepsilon_{rv} \times A_r \times F_{rv}\left(T_v^4 - T_{ra}^4\right)\right]$

   Where ,

σ = Stefan-Boltzmann constant $= 5.67 \times 10^{-8} W/m^2 K^4$

ε_{pv} = Emissivity factor for pulse tube and vacuum vessel

$= [(1/\varepsilon_p) + (1/\varepsilon_p - 1)(A_p/A_v)]^{-1} = [(1/\varepsilon_p) + (1/\varepsilon_p - 1)(D_p/D_v)]^{-1}$

ε_{rv} = Emissivity factor for regenerator and vacuum vessel

$= [(1/\varepsilon_r) + (1/\varepsilon_v - 1)(A_r/A_v)]^{-1} = [(1/\varepsilon_r) + (1/\varepsilon_v - 1)(D_r/D_v)]^{-1}$

F_{pv} = Shape factor for pulse tube and vacuum vessel of cylindrical geometry $= 1$

Frv = Shape factor for regenerator and vacuum vessel of cylindrical geometry $= 1$

Tv = Temperature of vacuum vessel = 303 K

T_{pa} = Average temperature of pulse tube = $[274.4 + 265]/2 = 269.7$ K

T_{ra} = Average temperature of regenerator= $[266.1 + 312.8]/2 = 289.45$ K

Therefore,

$= 5.67 \times 10^{-8}[(0.132 \times \pi \times 14.9 \times 10^{-3} \times 0.300)] \times (303^4 - 269.7^4) + (0.128 \times \pi \times 19.2 \times 10^{-3} \times 0.2)] \times (303^4 - 289.45^4)]$

$= 2.63$ W

6. Net refrigeration power

=gross refrigeration power - various losses

$= 10.33 - [0.067 + 0.25 + 0.007 + 0.125 + 2.63]$

$= 7.25$ W

Appendix - B
Wire Mesh Area in Regenerator

For,

n =no. of wire mesh require= 1500

A_r =internal cross sectional area

so,

Total requirement of wire mesh area

$A_r \times 1500 \times 1.5$

$= \left(\frac{\pi}{4} d_{ri}^2\right) \times 1500 \times 1.5$

$= \left(\frac{\pi}{4} (0.016)^2\right) \times 1500 \times 1.5$

$= 0.46 m^2$

$= 4.84$ sq. ft

≈ 5 sq. ft

Appendix - C

Vacuum Pump Down Time

For,

T =time

V =volume of system (liters) = 45.8 liter

S =speed of pump (constant pumping speed is assumed) = 1440

P_1 =initial pressure = 1 mbar

P_2 =ultimate pressure require = 0.1 mbar

$T = 2.3\left(\frac{V}{S}\right)\log\left(\frac{P_1}{P_2}\right)$

$= 2.3 \times \left(\frac{45.8}{1440}\right)\log\left(\frac{1}{0.1}\right)$

$= 0.073$ hr

$= 4.39$ min (for constant motor speed and neglecting leakage)