EXPERIMENTAL ANALYSIS ON PULSE TUBE REFRIGERATOR

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Abstract: The absence of moving components at low temperature end gives the pulse tube refrigerator (PTR) a great leverage over other cryo-coolers like Stirling and GM refrigerators that are conventionally in use for several decades. PTR has greater reliability; no electric motors to cause electromagnetic interference, no sources of mechanical vibration in the cold head and no clearance seal between piston and cylinder. Moreover, it is a relatively low cost device with a simple yet compact design. The objectives of the present work are to understand the basic phenomena responsible for the production of cold effect with the help of simple theoretical models based on ideal behavior of gases and to test a single stage GM type pulse tube refrigerator. Experimental studies consist of cooling behavior of the refrigeration system and suggesting modifications to improve the performance of the PTR.

***Keywords*- Pulse Tube Refrigerator, Regenerator, RTD Scanner System, Leak Test, Cool down Characteristics, Coefficient of Performance.**

I. INTRODUCTION TO PULSE TUBE REFRIGERATORS

In the pulse tube refrigerator, the displacer is eliminated. The proper gas motion in phase with the pressure is achieved by the use of an orifice and a reservoir volume to store the gas during a half cycle. The reservoir volume is large enough that negligible pressure oscillation occurs in it during the oscillating flow. The oscillating flow through the orifice separates the heating and cooling effects. The orifice pulse tube refrigerator (OPTR) operates ideally with adiabatic compression and expansion in the pulse tube.

The four steps in the cycle are as follows.

- The piston moves down to compress the gas (Helium) in the pulse tube.
- Because this heated, compressed gas is at a higher pressure than the average in the reservoir, it flows through the orifice into the reservoir and exchanges heat with the ambient through the heat exchanger at the warm end of the pulse tube. The flow stops when the pressure in the pulse tube is reduced to the average pressure.
- The piston moves up and expands the gas adiabatically in the pulse tube.
- This cold, low-pressure gas in the pulse tube is forced toward the cold end by the gas flow from the reservoir into the pulse tube through the orifice. As the cold gas flows through the heat exchanger at the cold end of the pulse tube it picks up heat from the object being cooled. The flow stops when the pressure in the pulse tube increases to the average pressure. The cycle then repeats.

II. EXPERIMENTAL SET-UP

The schematic of the experimental set-up is as shown in the figure below. The whole experimental set-up can be divided into four units namely the compressor unit, the pressure wave generating unit, the cold box unit and the data acquisition system. The compressor unit consists of the compressor, the after cooler and the oil filters. The low-pressure working fluid is compressed to a high pressure in the compressor. The after cooler removes the heat of compression and brings the working fluid to near-ambient temperature. The working fluid then passes through the oil filters where the oil and other fine impurities are removed. The suction and discharge ends are connected to a rotary valve that consists of a synchronous motor that is actuated by an electrical frequency varying unit.

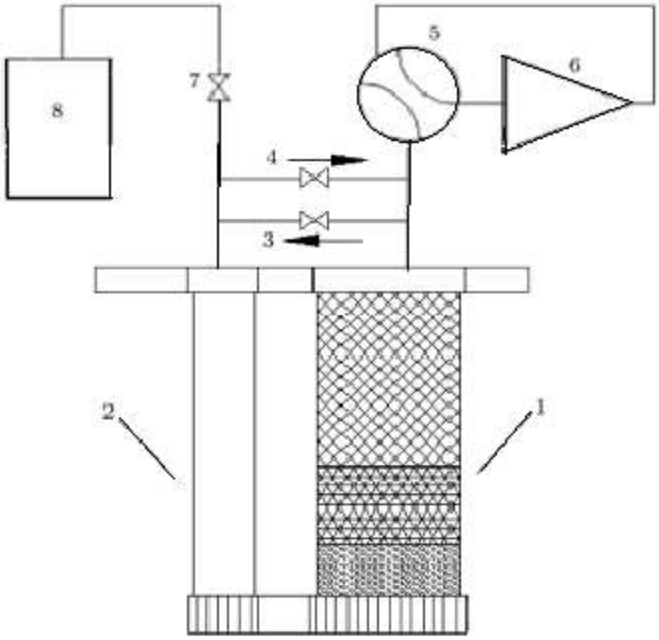

Fig. 2.1: Schematic of the experimental set-up

The regenerator and pulse tube are connected to these valves as shown in figure 2.1. The regenerator, pulse tube and the heat exchangers are placed in an evacuated vessel, normally known as the cryostat or the cold box. The cold end of the pulse tube has provisions for fixing a heater wire and a Platinum resistance thermometer (PT 100). In the pulse tube heat is intermittently transferred from the cold end to the warm end heat exchanger Cold water, cooled in a water bath, cools the warm end heat exchanger. A buffer volume is attached to the warm end of the pulse tube through a metering valve. The cryostat is maintained at a pressure of 10-4 mbar so as to minimize the heat leakage from the ambient. Multilayer insulation is used to reduce the heat leak from ambient. A number of pressure transducers and temperature sensors have been located at critical positions in the set-up. All electronic sensors are connected to the data acquisition system, which helps to digitally monitor and store data.

III. COMPONENT DESCRIPTION

Compressor Unit:

The compressor used is single-stage oil lubricated hermetically sealed reciprocating compressor. A thermal overload protector, attached to the compressor prevents overloading by switching off upon overheating. The compressor is water cooled to remove the large amount of heat produced during compression of Helium. The oil used in the compressor may get carried over to the cold box where it can freeze and foul the pipes, pulse tube and the regenerator. Superior quality coalescing filters followed by activated charcoal bed have been used. The oil filters are of Domnick Hunter, UK make. Oil, collected in the oil filters, is periodically sent back through a solenoid valve. Solenoid operated automatic by-pass valve has also been provided.

Table 3.1: Specifications of compressor

Make	Kirloskar Copeland Limited
Suction Pressure	6 bar
Discharge Pressure	28 bar
Flow rate	8 m3/hr
Voltage rating	400 V – 3 Phase – 50Hz,
Size	710mm x 585mm x 510mm
Weight	80 kg
Gas	Commercial Helium

Rotary Valves:

The rotary valve is one of the critical components of most cryo-coolers such as Gifford Mc-Mahon and pulse tube. It is used to switch between high and low pressures from a helium compressor to the required system. In most commonly used valves the rotor is pressed tightly against the stator and large driving torques are needed.

Electrical Frequency Varying Unit:

The electrical frequency varying unit serves the purpose of varying the frequency of the electrical supply to the synchronous motor attached to the rotary valve. Hence it controls the speed of the motor which varies the frequency of the pressure wave fed to the pulse tube. Synchronous speed is given by,

$Ns = 120*f/p$

F – Frequency of the electrical signal

P – No of poles of motor

It consists of many components like integrator, potentiometers, FET switches, microcontroller etc. integrated on a printed circuit board.

Regenerator:

Regenerator was made of stainless steel tube filled with 200 mesh size stainless steel meshes. The tube is of length 200mm and of inner diameter 17.6mm. The tube was machined to reduce its thickness to 0.5mm to reduce axial heat conduction. The meshes were machined by turning process so that they fit exactly into the tube. The meshes were closely packed into the tube. Stainless steel meshes were used because they have high heat capacity and provide a large surface area for heat transfer.

Pulse tube:

Pulse tube was made of stainless steel tube of length 300mm and of inner diameter 12.7mm. It was also machined to reduce thickness to 0.5mm. The pulse tube is bounded by a warm-end heat exchanger and a cold-end heat exchanger.

Cold-end Heat Exchanger:

It is brazed to the cold end of the pulse tube. Made out of a copper rod it has provisions for Pt 100s and a heater wire. It is packed with Copper meshes (mesh size 200) for enhanced heat transfer between the working fluid and the load.

Warm-end Heat Exchanger:

It is connected to the warm end of the pulse tube. It is a wire mesh heat exchanger. It is made of two co-axial stainless steel tubes filled with stainless steel wire meshes. The working fluid flows in the inner tube. Cold water from a water bath is pumped through the shell side of the heat exchanger.

Buffer Volume:

It is connected to the warm-end heat exchanger through a metering valve. It is a two liter stainless steel cylinder. The buffer volume was chosen to be greater than ten times the volume of the pulse tube.

Cryostat:

The regenerator, pulse tube and the heat exchangers are enclosed in a cryostat and maintained at a vacuum of approximately 0.01 mbar. This almost fully eliminates the infiltration of heat by convection. No part of the cold end should be in contact with the cryostat. This helps avoid heat infiltration.

Table 3.2: Details of Cryostat

Material	SS304
Leak Rate	< 10-6 Torr-lit/sec
Length	484 mm
Diameter	300 mm
Outlets from the flange	4 nos (3/4 ” dia 100 mm long)

RTD Scanner System:

The temperature sensor connected to the RTD scanner system, which helps to digitally monitor and store the data. Temperature of the cold end is measured using Platinum resistance thermometer (Pt 100s) for accurate measurements. It was calibrated and used in the four-wire system for improved accuracy. A 24 V DC supply is used as the power source for the transducers. An electrical feed-through has been used to preserve vacuum while making the electrical connections from inside the cryostat to the data-logger. An aluminium transition piece has been fabricated and used for fixing the electrical feed-through to the cryostat.

Fig 3.1: Pictorial view of the Data Acquisition System

Fig. 3.2: Pictorial view of regenerator and pulse tube

Fig. 3.3: Pictorial view of electrical unit

Fig. 3.4: Pictorial view of rotary valve

Fig. 3.5: Pictorial view of compressor

IV. LEAK TEST

First the system was charged with nitrogen and checked for leaks using soap solution. Later it was filled with small quantity of helium and a helium leak detector was used. Leaks were found in the compressor unit especially in the pressure gauges and in the bypass valve. These components were replaced and all other leaks were plugged so that the leak was minimized to be within the allowable limits.

V. EXPERIMENTAL PROCEDURE

The cryostat is connected to the vacuum pump and the vacuum pump is switched on until the vacuum within the cryostat is of the order of 1x10-4 mbar. The pulse tube refrigerator is evacuated and then filled with the working fluid to appropriate pressure. The water bath is switched to cool the water. The electrical switching unit is adjusted to produce the required pressure wave. The metering valves are also adjusted according to requirements.

The setup is started by switching on the compressor and the electrical switching unit. The pressure ratio is controlled by adjusting the bypass valve. The pump circulates the water through the warm-end heat exchanger. The setup is run at no load until steady state is achieved. The temperature values are continuously monitored by the data acquisition system.

VI. RESULTS AND DISCUSSIONS

Generation of Pressure Pulse:

The primary task was to create a sinusoidal pressure wave in the regenerator and pulse tube. This was achieved using rotary valves controlled by electrical unit. Experiments were conducted with optimum pressure range of 5 bars – 12 bars. Frequencies of 1 Hz and 2 Hz were used during experiments.

Effect of Valve Opening:

The performance of the pulse tube refrigerator primarily depends upon the phase relationship between pressure and mass flow. This phase relationship is dependent on many parameters like pulse tube volume, orifice valve opening, bypass valve opening and frequency of pressure pulse. Several experiments were done to reach an optimum configuration with respect to the no load temperature. Figures 6.1 and 6.2 shows the effect of valve opening on the performance of pulse tube refrigerator.

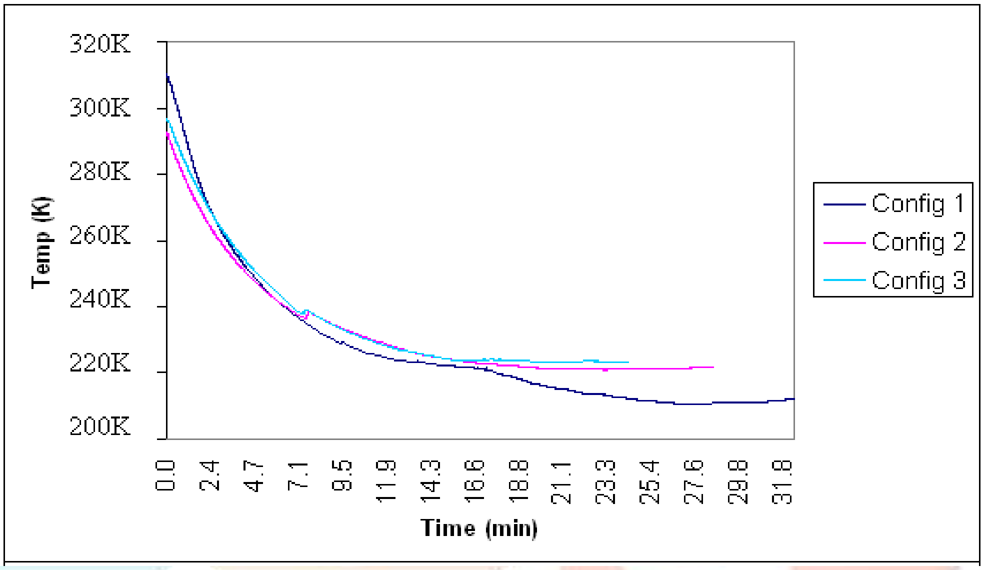

Fig. 6.1: Cool down characteristics for different orifice valve openings

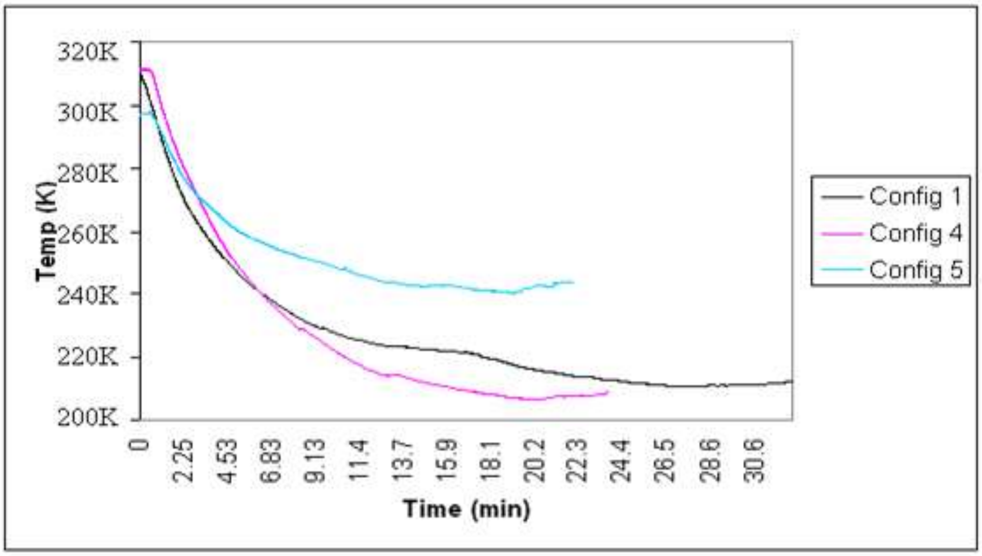

Fig. 6.2: Cool down characteristics for different bypass valve openings

Table 6.1: Configuration description

Configuration	Orifice valve opening (as read on the metering scale)	Bypass valve opening (as read on the metering scale)	COP (on load)
Configuration 1	7	0	3.5
Configuration 2	14	0	3.4
Configuration 3	21	0	3.56
Configuration 4	7	10	4.03
Configuration 5	7	20	3.8

Table 6. 2: No load temperature attained

Configuration	No load temperature(K)
Configuration 1	245.21
Configuration 2	250.00
Configuration 3	241.55
Configuration 4	213.28
Configuration 5	226.11

The results show that no load temperature obtained is strongly dependent on opening of the orifice and bypass valves. It is clear that there is an optimum value for the valve openings. When the orifice valve is opened there is a drop in its resistance and thus the performance of PTR changes. It is observed that performance of orifice pulse tube refrigerator can be improved by introducing a bypass valve. Introduction of the bypass increases the amplitude of the pressure fluctuation on the cold side of the pulse tube and reduces the phase angle, with clear effects on the performance. The results are seen to be quite sensitive to the bypass resistance. Large opening of the bypass valve has negative effect on the performance. Overall the results reveal a complex behavior with respect to the orifice and bypass adjustments, which can be attributed to the fact that instantaneous division of flow between the two parallel paths depends upon the instantaneous impedances of the two paths.

Effect of Frequency:

Experiments were conducted with frequencies of 1 Hz and 2 Hz with Nitrogen as working fluid. The results are shown in figure 6.3.

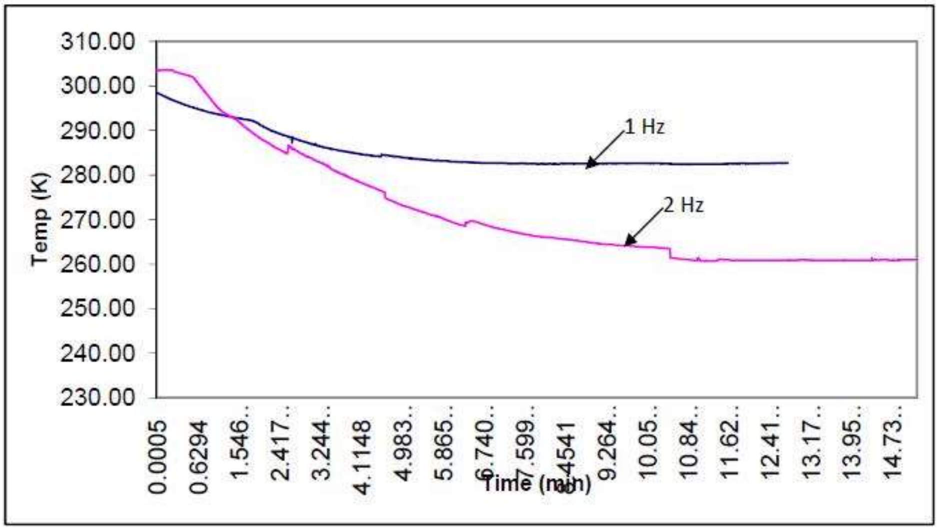

Fig. 6.3: Cool down characteristics for different frequencies

Pulse tube refrigerator works at low frequencies. Frequency defines the diffusion depth in the working fluid and the regenerator material. When frequency is increased diffusion depth decreases and the heat storage in the regenerator degrades. High operating frequency means a big pressure drop in the regenerator, which leads to a poor performance. Hence low frequencies (1 Hz and 2 Hz) were used. It was observed that with a frequency of 2 Hz lower no load temperature could be achieved. This can be attributed to the fact that higher frequency increases time averaged enthalpy flow.

VII. CONCLUSIONS

- A pulse tube refrigerator has been built and tested with different valve openings. The proof of concept has been established.
- Lowest no load temperature obtained is **213 K**.
- COP obtained on applying load is **4.03.**

VIII. MODIFICATIONS SUGGESTED

- Optimization of pulse tube and regenerator dimensions as well as arrangement of regenerator material to achieve lowest possible temperature.
- Incorporation of an inertance tube to enhance the performance of pulse tube refrigerator.
- Vortex tube arrangement can be used inside the pulse tube to avoid mixing of cold and hot gas.

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