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Development and Experimental Investigations on Two Stage GM Type Pulse Tube Refrigerator for 20 K Applications

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Abstract. Because of the absence of any moving components at the cold region, low vibration and high reliability, two stage GM type pulse tube refrigerator (PTR) is nowadays preferred compared to conventional GM refrigerator for cooling of superconducting magnets, SQUIDs, and cryopumping applications. The second stage regenerative material plays an important role in achieving low temperature below 20 K. Leads balls with 0.2 mm to 0.4 mm average diameter was selected as second stage regenerator matrix material while 200 mesh of SS 304 material was filled in the first stage. A two stage GM type PTR was developed. A rotary valve was fabricated and the valve timing effects on cooling performance of PTR were also studied. The valve timings were varied by the different width of rotor slit forming the flow area with stator ports. The lowest no-load temperature of 18.52 K and cooling capacity of 7 W at 29.58 K were obtained with an optimum frequency of 1.6 Hz, charging pressure of 16.5 bar.

1. Introduction

The pulse tube refrigerator was invented by Gifford and Longsworth [1] in the early 1960s followed by improvement in basic pulse tube refrigerator by Mikulin et al. [2] in 1983 which is known as orifice pulse tube refrigerator. The last and major improvement was done by Zhu et al. [3] in the early 1990s which are nowadays called as double inlet pulse tube refrigerator. Because of the absence of any moving parts in a cold expansion space, pulse tube refrigerators are now considered as most reliable due to vibrationless and maintenance free operation and replacing conventional GM refrigerators for many similar applications. These applications include cryo-pumping, cooling of superconducting magnets/devices, Infrared detectors which require a temperature of the order of 10-20 K. For these applications, 4 K PTC refrigerators are commercially available and which are very costlier because of rare earth materials used in second stage regenerator. On the other hand, it can be possible to produce temperature about 20 K by use of cheaper lead shots as second stage regenerator material instead of costlier rare earth magnetic materials. These 20 K cryo-refrigerators are ideally suitable for the applications mentioned above.

The initial work on pulse tube refrigerator was reported by Narayankhedkar et. al. [4] in the early 70's. Naik et. al. [5,6] have presented the phasor analysis of pulse tube refrigerator. Atrey and

Narayankhedkar [7] developed second order isothermal model for orifice pulse refrigerator with the linear compressor. Karunanithi et. al. [8] developed a single stage double-inlet pulse tube refrigerator. They obtained the no-load temperature of 90 K from preliminary experiments. Development of single-stage pulse tube refrigerator was at S V National Institute of Technology, Surat under two sponsored projects from the Department of Science and Technology, New Delhi. Refrigeration power of 40 W was measured at 77 K temperature and 28 K no load temperature was measured. Kasturirangan et al. [9] have developed a two-stage Pulse Tube Refrigerator which produces a no-load temperature of around 2.8 K and delivers a refrigeration power of 250 mW at 5 K. They have used 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..

It is observed that for a low-temperature range of 10 K to 20 K, regenerative material lead shots (balls) in second stage regenerator for Two-Stage GM Type Pulse Tube Refrigerator are sufficient. There is no need to use the costly rare earth magnetic material to obtain no load temperature about 20 K applications. Thus, present work focuses on the development and experimental investigation of two stage GM type pulse tube refrigerator for 20 K Applications.

2. Development of an experimental setup

The complete experimental setup is developed based on the numerical method given in [10]. The numerical analysis was performed with initial dimensions of 4 K GM type pulse tube refrigerator which is already present in the laboratory. By varying the length of the second stage pulse tube, the lowest temperature at the second stage cold end was estimated. The second stage no-load temperature of 15.24 K was obtained to achieve temperature less than 20 K experimentally. The final dimensions of each component are as shown in figure 1. The experimental setup for two stage GM type pulse tube refrigerator involved the development of a rotary valve, pulse tube and regenerator assembly, vacuum jacket and reservoirs.

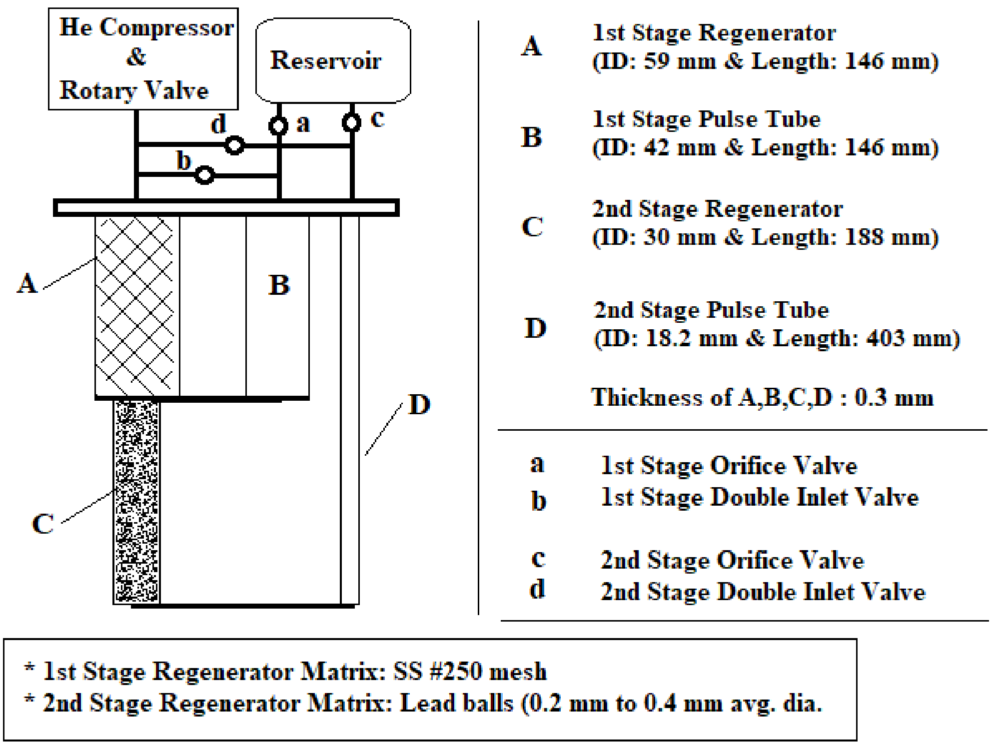

Figure 1. Overall schematic of the two stage GM type PTR

3. Results and discussion
The overall aim of the experimental investigations is to find the optimum performance of a system in terms of No load temperature and cooling capacity. The complete experimental investigations were carried out to study the 2nd stage cooling performance. With the given valve timing and charging pressure, the system was run with different operating frequency and phase shifter openings.

3.1 Effect of valve timing on system performance
The experimental investigations on valve timing diagram include the effect of intake time on no-load temperature and cooling capacity. The rotor has two slits 'c' &'d' for gas to flow. The different valve timing diagram can be obtained by changing the rotor slit size 'c' or 'd'. The present work involves the experimental investigations on valve timing diagram by a change in the width of the slit 'c' to get different timing ratio. The diameter of the stator channel 'a' is 'D' (figure 2).

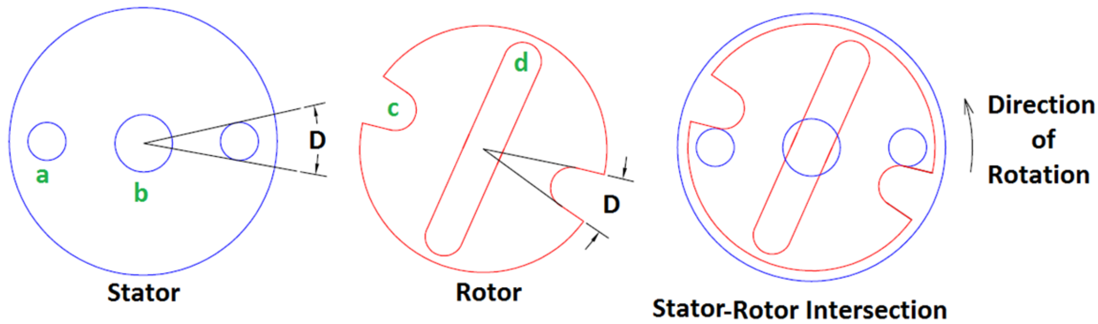

Figure 2. Different geometry of rotor for different valve timings

The tangent to this channel makes an angle of 27° for 'D' case (case-1). The corresponding slit 'c' on the rotor is cut such that the included angle between side edges of the slit 'c' becomes 27°. Thus, the communication between the stator and rotor becomes 27°+27°=54°. Thus, the gas can enter into the system for 54° time duration and this is called the pressurization period. This case with 54° pressurization time is referred to as Rotor-D case (figure 2). Similarly, by changing the size of rotor slit 'c' such that the total included angle between side edges becomes 37° (which is included angle between tangents at stator channel 'a' with 1.5D size). This makes total pressurization time 27°+37°=64° because of the increased width of the rotor slit 'c'. This case is referred to as Rotor-1.5D (case-2). Similarly, pressurization time in Rotor-2D case-3 becomes 27°+45°=72°.

In double inlet mode, with Rotor-2D case, the lowest no-load temperature of 18.52 K was obtained with 16.5 bar charging pressure and 1.6 Hz optimum frequency (figure 3). With the given parameters, 1 W of cooling capacity was obtained at 19.61 K temperature and 7 W of cooling capacity was obtained at 29.58 K temperature (figure 4). The pressure ratio obtained at starting condition and at steady state condition in all the valve timing case reveals that better pressure ratio was recorded with Rotor-2D case. The flow area created during the opening of the rotary valve plays an important role. At the steady state where the lowest temperature is created, the mass flow requirement is highest and this requires more gas to flow in and out in a given time. Thus, providing more flow area with 2D rotor compared to D & 1.5D case gives the better pressure ratio and better cooling capacity. From the simulation value, it is observed that the predicted temperature of the 2nd stage cold end with 1.5D, 2D and 2.5D case is almost constant and shows little variation. Thus, valve timings were only studied with three cases D, 1.5D and 2D experimentally.

The investigations in orifice mode and double inlet mode included the effect of the orifice and double inlet area on no-load temperature, the effect of the orifice and double inlet area on no-load temperature profile, the effect of charging pressure on no-load temperature and effect of operating frequency on no-load temperature. There exist an optimum orifice area and double inlet area which gives the lowest No Load temperature.

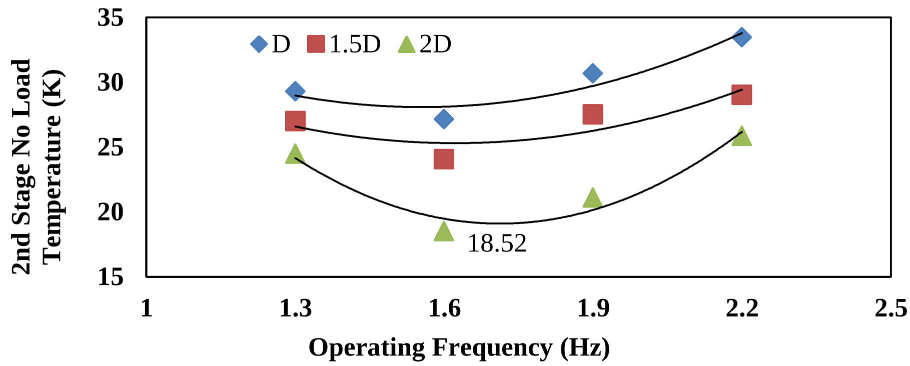

Figure 3. Effect of valve timing on 2nd stage No load temperature (P_{charge}: 16.5 bar)

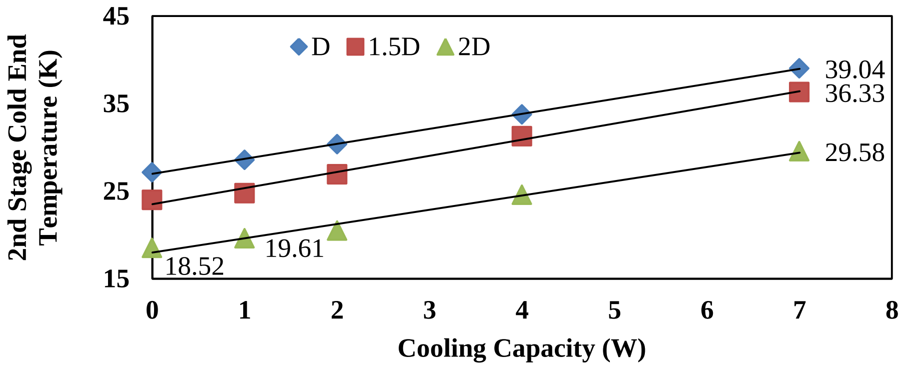

Figure 4. Effect of valve timing on refrigeration power (P_{charge}: 16.5 bar, Frequency: 1.6 Hz)

Optimum orifice area at higher frequency is higher compared to that of lower operating frequency. This is due to the fact that at a higher frequency, the cycle time decreases and less time is available for gas to flow through the orifice. To compensate for the reduction in flow through an orifice at a higher frequency, orifice area should be larger as compared to that of lower frequency operation. Too low orifice opening does not allow the much gas to pass through in a reservoir in a given time and thus, phase angle shifts away from the optimum phase. The Too large opening allows more gas to pass and makes the gas displacement larger and it disturb the gas piston formed inside the pulse tube.

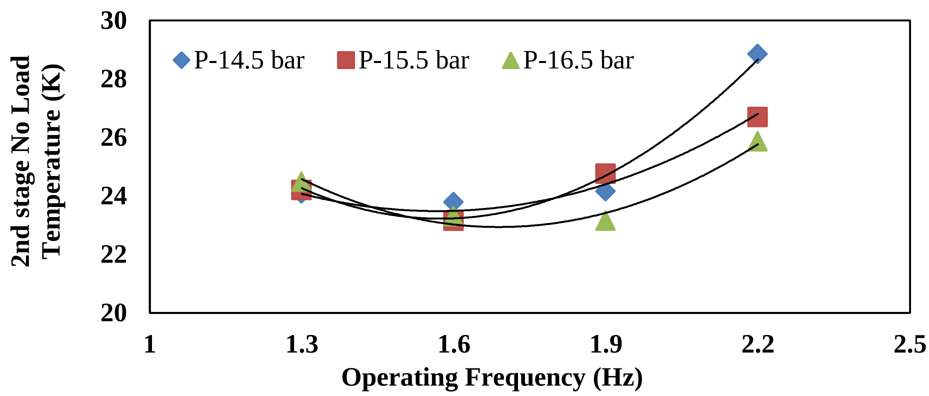

Figure 5. Effect of charging pressure on 2nd stage No-load temperature (Rotor: 2D)

3.2 Effect of operating frequency and charging pressure

The operating frequency changes the heat transfer time during a cycle. Lower frequency gives higher heat transfer time and higher frequency gives lower time. Higher frequency operation

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creates turbulence at the cold end of the pulse tube at each stage and increases the pressure drop in the regenerator. Thus there exists an optimum frequency at which system gives a better cooling performance. The present investigations were done with three different charging pressures with appropriate phase shifting openings as shown in figure 5. The optimum charging pressure of 16.5 bar was found where no load temperature at 2^{nd} stage pulse tube was lowest and cooling capacity obtained is higher than other charging pressure. Further increment in charging pressure is not possible due to compressor limitation. It is observed that the optimum operating frequency does not change with respect to the charging pressure. The optimum performance in the double inlet at 1.6 Hz frequency and the valve timing of Rotor-2D give minimum temperature at 16.5 charging pressure.

Conclusions
An experimental setup of a two stage GM type pulse tube refrigerator was developed to study the performance with a change in different operating parameters. The purpose of the development of two stage GM type pulse tube refrigerator was to obtain the temperature suitable for 20 K applications. The lowest No-load temperature of 18.52 K was obtained at 2nd stage cold end with 1.6 Hz optimum operating frequency, 16.5 optimum charging pressure and the optimum valve timing of 2D in double inlet mode. The optimum cooling capacity of 1W at 19.61 K and 7 W at 29.58 K was obtained with the optimum frequency of 1.6 Hz, optimum charging pressure of 16.5 bar and 2D rotor valve timing case. The performance of the first stage was poor compared to the second stage. The lowest No load temperature of 195. 95 K was obtained with the 2.2 Hz operating frequency and 16.5 bar charging pressure.

Acknowledgment
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