INVESTIGATION ON THERMAL COUPLED THREE STAGE PULSE TUBE CRYOCOOLER

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Pulse Tube Cryocoolers (PTCs) have been investigated in recent times with the focus on achieving much lower temperature and reliable operation. Lower temperatures can be obtained by cascading the stages of the PTC. These stages can either be gas coupled or thermal coupled. This paper presents the design and development of two different configurations of three stage thermal coupled PTC, one with room temperature phase shifting mechanism (PSM) and the other with cold phase shifting mechanism. For room temperature PSM, the first and second stage are provided with inertance tube, while that for the third stage is provided with inertance tube and a double inlet valve. For the cold PSM, only an inertance tube is used as a phase shifter. In case of PTC with room temperature PSM, a minimum temperature of 19.61 K is achieved with a refrigerating effect of 220 mW at 30 K at the cold end of the third stage pulse tube, with an input power of 600 W. While for the PTC with cold PSM, a minimum temperature of 32.41 K is achieved. A reliability test is carried out; the PTC performed well during the entire operation and the repeatability is established.

Key words: Phase Shifting Mechanism, Thermal Coupled, Multi-stage, Pulse Tube Cryocooler

INTRODUCTION

Pulse tube Cryocooler (PTC) is a closed system device which produces refrigeration effect at cryogenic temperature. Absence of moving parts at the cold end makes the operation of PTC vibration free and highly reliable. The simplicity in fabrication makes cascading of the stages (multi-staging) easy. This enables the PTC to achieve much lower temperature (below 20 K) with an input power of a few hundreds of watts. The multi-staging of the PTC can be done either by thermal coupling or by gas coupling of the stages.

In a PTC, different mechanisms are used to obtain an optimum phase difference between the pressure pulse and the mass flow rate at the cold end of the pulse tube. An optimum phase difference between the pressure and the mass flow rate is required to improve the PTC performance. Different types of phase shifters like orifice valve, inertance tube, double inlet valve with inertance tube, cold phase shifter etc. can be employed to optimize the performance of a PTC. The orifice valve is useful as a phase shifter in low frequency Gifford Mc-Mahon type PTC. In multi-stage Stirling type PTC, the double inlet valve with inertance tube or cold phase shifters are generally used.

The double inlet valve bypasses some part of the gas from compressor, which otherwise would flow in to the regenerator, directly to the pulse tube. This increases the pressure ratio in the pulse tube and affects the phase shift, thus improving the performance of the PTC. However, when a closed loop flow path exists in a PTC, there is a potential for a DC gas flow which degrades the performance of the PTC [1]. The cold phase shifters provide a large phase shift, which is necessary for the optimized performance of the multi-stage regenerator with a small inlet PV power. However, it adds cooling load on the system and intertance tube optimization becomes difficult in this case.

Research work related to multi-staging of PTC to achieve temperature below 20 K has been reported by different researchers around the world [2-6]. Most of them used lead and rare earth material as regenerator material. However, these are restricted from use due to health and cost considerations. The present work reports the design and development of a three stage Pulse Tube Cryocooler to achieve temperature below 20 K without using lead or rare earth material.

Theoretical and experimental investigation on single stage U type PTC has been reported by Badgujar and Atrey [8]. They have also reported work on design and development of Stirling type two stage PTC, with double inlet (DI) valve as phase shifter [9]. The DI valve may generate a DC flow (which flows in a loop between DI valve, pulse tube and regenerator) leading to an unsteady cooling performance. The DC flow can be avoided by using cold PSM where no DI valve is used. Gan et. al. [10] have reported a refrigerating effect of 0.5 W at 33.9 K on two stage PTC using cold PSM.

This paper reports design and development of two different configurations of three stage thermally coupled PTCs. In one case, warm PSM is incorporated while in the other case, cold PSM is used. Both these PTCs are operated by two different compressors with input power of 300 W to each compressor.

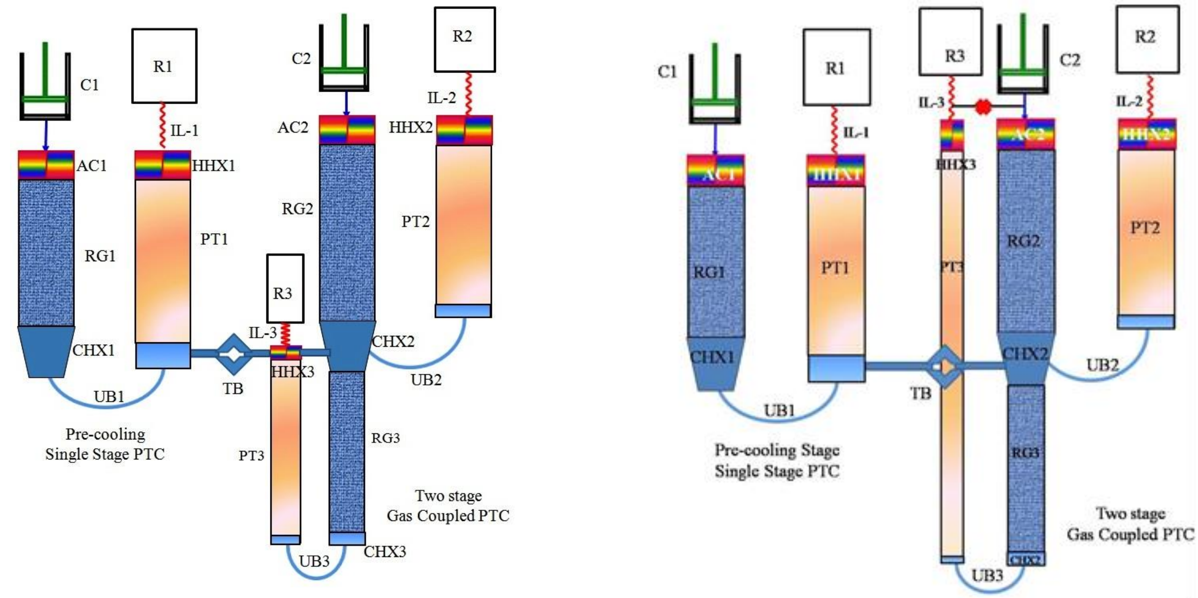
THREE STAGE PTC WITH COLD AND WARM PHASE SHIFTING MECHANISM

Three stage PTC with cold phase shifter

Figure 1a shows schematic of three stage PTC with cold PSM. The hot end heat exchanger (HHX3), the inertance tube (IL3), the reservoir (R3) at the third stage and second stage cold end (CHX2), are pre-cooled by the cold end of the first stage of three stage thermal coupled PTC as shown in figure. Thermal link (TB) is used to transfer the refrigerating effect.

Three stage PTC with inertance tube warm phase shifter

The three stage PTC is designed using Isothermal model and Sage software [11]. The detailed design of a three stage thermal coupled PTC using Isothermal model and Sage software has been reported by Badgujar and Atrey [12], the schematic of the same is shown in Figure 1b. The first stage cold end of three stage PTC (CHX1) is coupled by thermal bridge (TB) to the second stage cold end (CHX2), and thus transfers cooling effect produced by the first stage.



(a) With Cold Phase shifter (b) with DI valve phase shifter [11]

Figure 1. Schematic of Three Stage Thermally PTC

COLD HEAD ASSEMBLY

The assembly of the cold head of the three stage thermally coupled PTC with DI valve as phase shifter is shown in Figure 2.

Figure 2. Assembly of Three Stage PTC

The cold end of first stage is coupled with cold end of second stage by a thermal bridge (TB) made of copper. Copper is used due to its high thermal conductivity in order to improve heat transfer between the PTCs. Double inlet valve with inertance tube is used as a phase shifter for the third stage, whereas the inertance tube is used as a phase shifter for the first and the second stage. The pulse tubes and the regenerators are made of SS 304 having thickness 0.15 mm. The regenerators consist of SS meshes with mesh size 400. The optimized dimensions of regenerator and pulse tube for the three stage PTC are given in Table 1.

Table 1 Dimensions of three stage PTC with Warm Phase Shifter

I.D x Thickness x length (in mm)

	Regenerator	Pulse Tube
Stage-1	28 X 0.15 X 54	12.2 X 0.15 X 74
Stage-2	16 X 0.15 X 60	8 X 0.15 X 60
Stage-3	9 X 0.15 X 60	4 X 0.15 X 140

The assembly of the cold head of the three stage PTC with cold PSM is similar to the one shown in Figure 2. In this arrangement, the hot end of the third stage pulse tube (HHX3), inertance tube (IL3) and reservoir (R3) are maintained at low temperature. The cooling effect is transferred by means of the thermal bridge (TB) to the cold phase shifters as shown in figure 1a. Table 2 gives the optimized dimensions of three stage PTC with cold phase shifters.

Table 2 Dimensions of three stage PTC with Cold Phase Shifter
I.D x Thickness x length (in mm)

	Regenerator	Pulse Tube
1st Stage	28 X 0.15 X 54	12.2 X 0.15 X 74
2nd Stage	16 X 0.15 X 55	8 X 0.15 X 60
3rd Stage	9 X 0.15 X 60	6 X 0.15 X 62

EXPERIMENTAL SETUP

Figure 3 shows the experimental setup of three stage PTC. Two linear compressors CFIC make, are used as a power source.

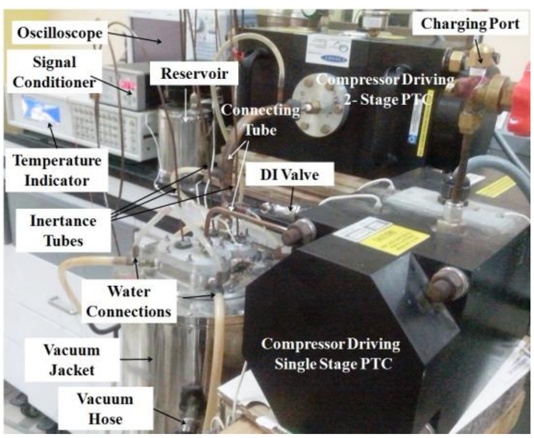


Figure 3. Experimental setup

ENDEVCO make piezoresistive transducers are used for dynamic pressure measurement. The dynamic pressure is amplified using ENDEVCO make DC differential voltage amplifier (Model 136) and recorded using Yokogawa make DL 750 oscilloscope. Silicon diode sensors are used for measuring temperature at cold end of the pulse tube.

RESULTS AND DISCUSSION

The following sections present detailed experimental investigations carried out on the three stage thermal coupled PTC, with cold phase shifters and with double inlet valve and inertance tube as phase shifters.

Cool-down Curve

Three stage PTC with cold phase shifter

Figure 4 shows the cool-down curve for the three stage PTC with cold PSM after optimizing various design and operating parameters. A minimum temperature of 32.41 K is obtained at the third stage of the PTC in this case. A temperature of 83.55 K is measured at the hot end of the third stage pulse tube and at the second stage, which are simultaneously cooled by the pre-cooling stage, as shown in Figure 1a. The pre-cooling stage (single stage) temperature remains at 69.21 K.

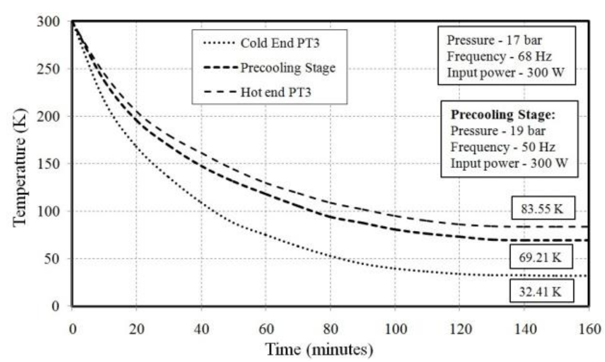


Figure 4. Cool-down Characteristics – PTC with cold Phase Shifting Mechanism

The PTC takes 150 minutes to reach the steady state temperature while it operates at a frequency of 68 Hz and a charge pressure of 17 bar, with input power of 300 W to each compressor. This higher cool-down time is due to the huge mass of cold phase shifters to be cooled, which consists of HHX3, IL3 and R3. The refrigeration effect provided by the first stage is found to be insufficient.

Three stage PTC with warm phase shifter

Figure 5 shows cool-down curve for the PTC. The two stage PTC operates at a charge pressure of 17 bar and at a frequency of 68 Hz, whereas the pre-cooling stage (single stage PTC) operates at a charge pressure of 19 bar and at a frequency of 50 Hz. After optimizing the length of inertance tube and double inlet valve opening, a minimum temperature of 19.61 K is recorded at the third stage.

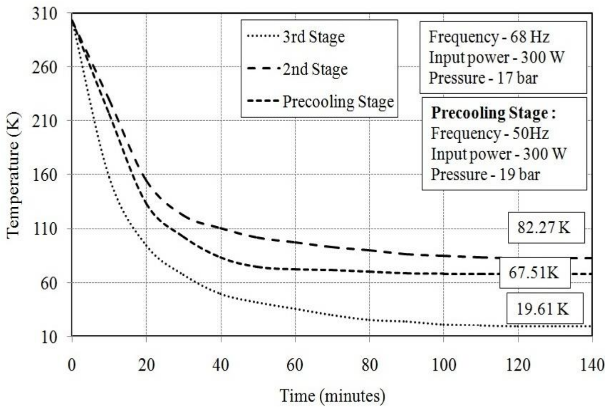


Figure 5. Cool-down Characteristics – PTC with warm Phase Shifting Mechanism

The temperatures across the thermal bridge (TB) are 82.27 K and 67.51 K for the second stage and the pre-cooling stage respectively. The temperature difference may be attributed to finite conductivity of copper, thermal contact resistance and small heat transfer area.

The cool-down time for this PTC is 120 minutes. The input power supplied is 300 W to each of the two compressors. The initial cool-down is comparatively fast and it takes about 70 minutes to reach a temperature below 30 K.

A refrigeration effect of 220mW at 30K is obtained at the third stage for an operating pressure of 17 bar with a compressor input power of 300 W to each compressor.

The cool down time is more in case of three stage PTC with cold phase shifter due to extra mass of the inertance tube, reservoir and the hot end heat exchanger to be cooled. Due to insufficient cooling power available from the pre-cooling stage, the PTC is not able to perform well. The above investigations suggest that the three stage PTC, having hot ends of pulse tube at room temperature which uses DI valve and inertance tube as phase shifter, yields the lowest temperature.

Reliability Test

Reliability test is carried out on the three stage PTC, with DI valve and inertance tube as phase shifters, by operating the three stage thermally coupled PTC for continuous two days (2 X 9 hrs). Figure 6 shows the temperature vs time curve for this PTC. The minimum temperature recorded is 19.71 K. The small oscillations observed in the minimum temperature are due to the on-off switching of the chiller system. The system is stopped after nine hours and is restarted on the next day which shows a repeat performance for all the stages.

CONCLUSION

The PTC with cold phase shifters could not perform very well and achieved a minimum temperature of 32.41 K, due to insufficient cooling power available from the pre-cooling stage. The single and two stage PTC are thermally coupled, with single stage PTC pre-cooling the two stage PTC, to build three stage thermally coupled PTC. A minimum temperature of 19.61 K with a refrigeration effect of 220 mW at 30 K is achieved at third stage cold end of the pulse tube for operating parameters of 17 bar charge pressure and 68 Hz operating frequency, with an input power of 300 W to each of the compressors. The reliability test is carried out by operating the PTC for continuous two days (2 X 9 hrs).

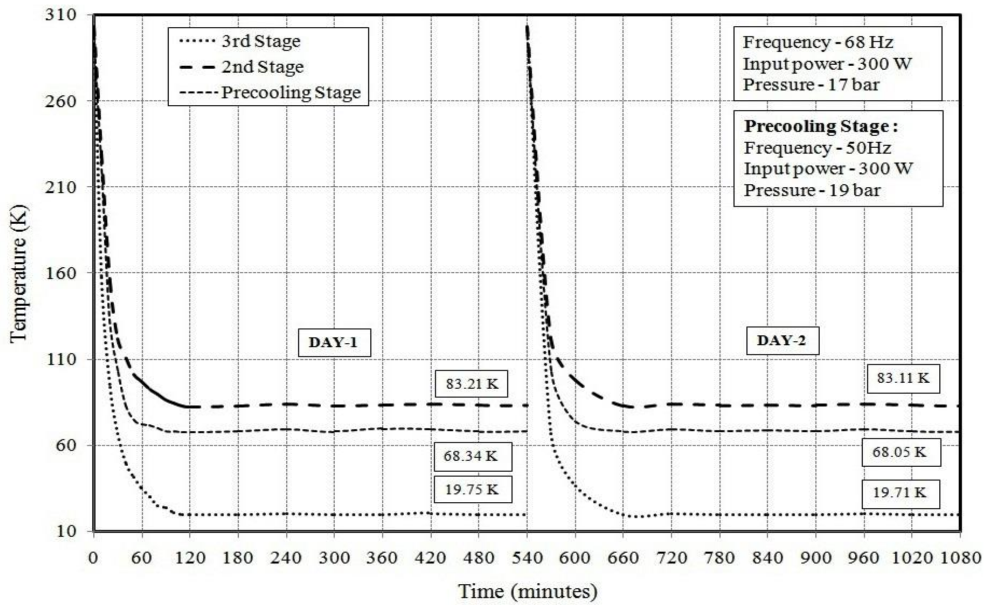


Figure 6. Reliability test on Three Stage thermal coupled PTC

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