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Experimental investigation on Stirling type thermally coupled three stage pulse tube cryocoolers with 'U' type configuration

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Abstract

Research on Stirling type Pulse Tube Cryocooler (PTC) is focused on achieving lower temperatures by cascading the stages or by multi-staging. Multi-staging can be done either by gas coupling or by thermal coupling of the stages. In the thermal coupling option, either a two stage cooler can pre-cool a single stage PTC to reach lower temperatures or a single stage PTC can cool a two stage PTC. In the present work, both these configurations are tested experimentally keeping the same two stage PTC. In case-1, the two stage PTC is used as a pre-cooling stage while in case-2, the single stage PTC is used as a pre-cooling stage. Length of the single stage is required and to be increased to match the two stages PTC for effective thermal coupling in case-1. The lowest temperature achieved in case-1 is 50.07 K where as in case-2 the lowest temperature achieved is 19.61 K at 17 bar charge pressure and 68 Hz frequency. The pressure drop in both the PTCs is compared to analyze the difference in performance.

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Keywords: three stage pulse tube cryocooler; thermally coupled; pressure drop

1. Introduction

Pulse tube cryocoolers (PTC) are devices used to generate and maintain very low temperatures, below 80 K. The research on PTC is focused on achieving much lower temperatures, which may be obtained by multi-staging of the

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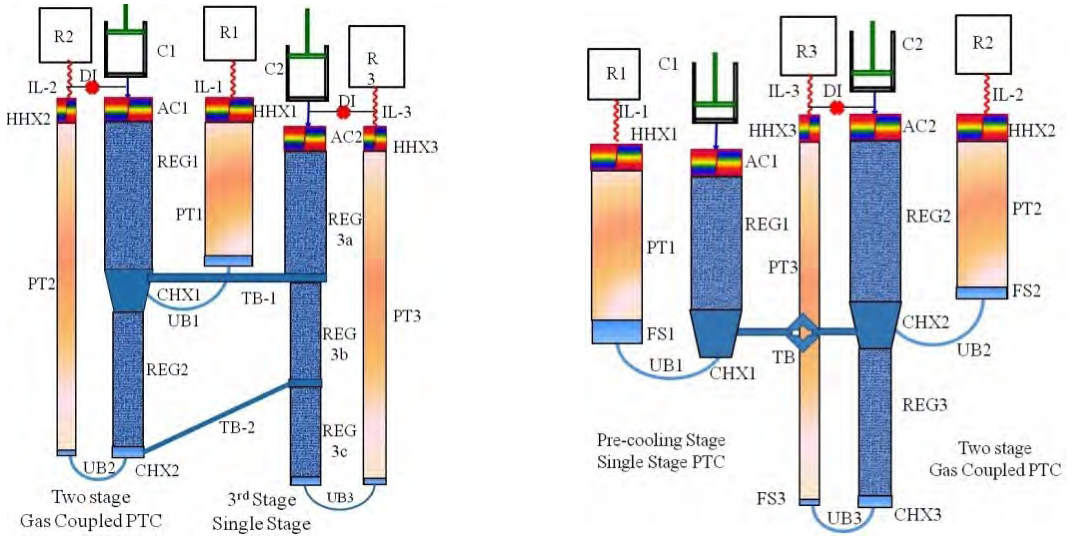
PTCs. The stages can either be gas coupled or thermally coupled. The Stirling type two stage PTCs are being investigated extensively during the last few years. Recently, a temperature below the critical point of helium is achieved by Qiu et. al. using $HoCu_2$ powder as regenerator material. The third stage operating frequency is 29.9 Hz for this PTC. An input power of 850 W is given to the first and the second stages. Zhi et.al., also have reported a temperature of 4.26 K with helium as a working fluid using rare earth material in a three stage PTC.

The single stage and two stage gas coupled PTCs were developed by Badgujar and Atrey achieving 55 K and 22.67 K, respectively. They have also recently reported the design and development of single stage, two stage and three stage pulse tube cryocoolers to achieve a temperature below 20 K. The present work reports the performance comparison of two different three stage PTC configurations based on thermal coupling of single stage and two stage PTC, without using lead or rare earth material in the regenerator.

2. Experimental setup

Fig. 1 shows the schematics of two different three stages thermally coupled PTC configurations. In both cases two independent pressure wave generators (C1, C2) are used to generate a pressure wave in two stage and single stage PTCs. In both cases the two stages PTC remains the same. As shown in Fig. 1a for case-1, the two stage PTC precools the single stage PTC. These stages are thermally coupled by means of thermal links TB-1 and TB-2. Based on the position of these thermal links the third stage regenerator is divided in three parts Reg 3a, Reg 3b and Reg 3c as shown in Fig. 1a. In case-2 the single stage PTC precools the two stage PTC they are coupled by a thermal link TB as shown in Fig. 1b. An experimental setup was developed for these PTCs to compare the performance of two different three stage PTCs.

Fig. 2 shows the experimental setup of developed PTCs with U type configuration. Pressure Wave Generator (PWG) of CHART is used to generate oscillating pressure waves in the PTC. Water-cooled recuperative heat exchangers, made of copper are designed to use as after coolers and to cool the gas at hot ends of respective pulse tubes. A Swagelok (SS-4MG-MH) valve is used as double inlet valve. ENDEVCO piezo-resistive transducers are used for pressure measurement; while silicon diode is used for temperature measurements.



a) Case-1: single stage as pre-cooling stage. b) Case-2: single stage as pre-cooled stage.

Fig. 1. Schematic of three stages thermally coupled PTCs.

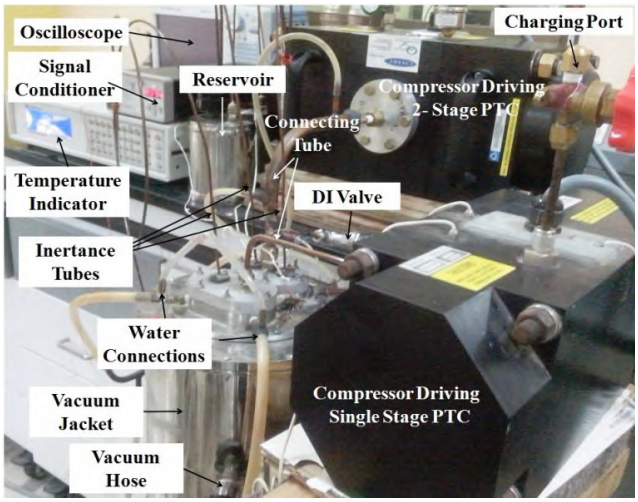


Fig. 2. Experimental setup for three stages thermally coupled PTCs.

An inertance tube with DI valve is used as a phase shift mechanism for the third stage. The pulse tubes and the regenerators are made of SS 304. The regenerators consist of SS 304 meshes with mesh size 400. The dimensions of various components of the PTCs are given in Table 1.

Table 1. Dimensions of different PTCs: inside diameter x length x thickness (in mm)

Sr. No.	PTC Unit	Stages	Regenerator	Pulse Tube
1	Two stage gas coupled PTC (Same in both the cases)	1st Stage	16 x 55 x 0.15	8 x 60 x 0.15
		2nd Stage	9 x 60 x 0.15	4 x 140 x 0.15
2	Single stage PTC for case-1	Reg 3a[1]	12 x 55 x 0.15	4 x 180 x 0.15
		Reg 3b[1]	8 x 65 x 0.15	
		Reg 3c[1]	6 x 43.5 x 0.15	
3	Single stage PTC for case-2	-	28 x 54 x 0.15	12.2 x 74 x 0.15

3. Result and discussion

Experimental investigations were carried out to study the effect of various operating and design parameters. To optimize the no load temperature, the helium charge pressure and the frequency of operation are varied in a certain range. The double inlet valve setting (number of turns) and the lengths of inertance tubes are also optimized. In the next sections experimental investigation of two different three stages thermally coupled PTCs is discussed in detail.

3.1. Single stage PTC pre-cooled by a two stage PTC (case-1)

This section presents an experimental investigation on three stage thermally coupled PTC, where a two stage PTC pre-cools the third stage i.e case-1. The two stage PTC is used to cool the regenerator of the third stage at two distinct points, as shown in Fig. 1a. The stages are thermally coupled by links TB-1 and TB-2, made of high conductivity material copper.

[1] Sections of single regenerator as shown in Fig. 1a for case-1

Cool down characteristics

Fig. 3a shows the cool down curve for case-1. In this case the two stages PTC operates at the charge pressure and frequency of 17 bar and 68 Hz and the third stage is operating at 17 bar and 70 Hz. The PTC takes 230 minutes to reach steady state temperature of 50.07 K at third stage, with input power of 200 W for the third stage and 300 W for the pre-cooling stage. The increase in input power beyond 200 W at the third stage degrades the performance.

The PTC achieves a minimum temperature of 84.61 K at the third stage when operated alone. This is due to very high pressure drop across the length of regenerator. Fig. 4a shows the pressure variation at the inlet to the regenerator and at the outlet of third stage pulse tube. The pressure drop measured is 2.65 bar. The high pressure drop at the third stage degrades the performance of the PTC. In this case, the load imposed by the third stage is much higher than the refrigeration effect produced by the two stages PTC. The two stage (pre-cooling) PTC achieves temperatures of 71.10 K and 133.04 K at the second stage and first stage respectively in thermal coupled mode as compared to 22.67 K and 89.52 K when operated independently.

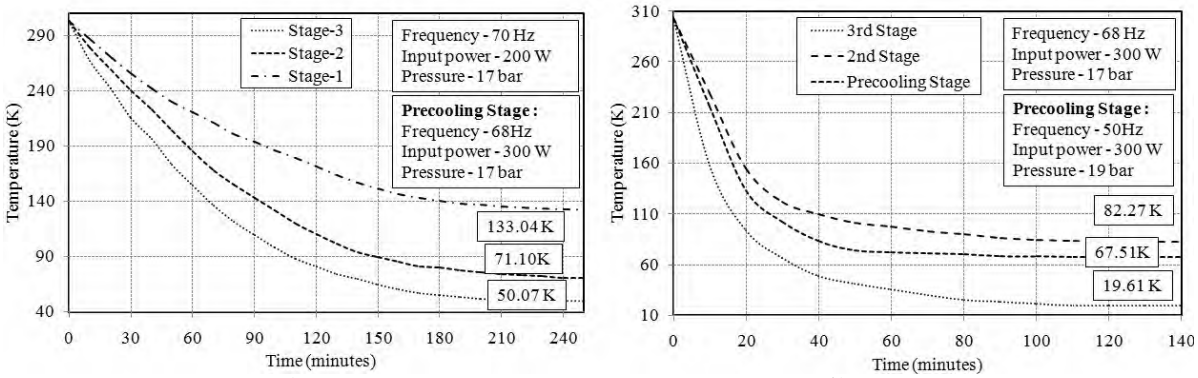
In order to achieve the no-load temperature below 20 K, a three stage thermally coupled PTC with another single stage as pre-cooling stage is designed and developed. The next section discusses the investigations on the same.

3.2. Two stages PTC pre-cooled by single stage PTC (case-2)

The length of the regenerator and pulse tube of single stage PTC is reduced (refer Table 1) in order to reduce the pressure drop across the regenerator. This is used as a pre-cooling stage for the two stages PTC, as shown in Fig. 1b. The pre-cooling single stage PTC achieves minimum temperature of 54.7 K and gives refrigeration effect of 6.1 W at 80 K with input power of 300 W. The performance of the single stage PTC in case-2 is far better than the single stage in case-1. The pressure drop measured between inlet to the regenerator and outlet to third stage pulse tube is 2.03 bar as shown in Fig. 4b. To optimize for no load temperature at third stage, the charge pressure and operating frequency are varied in a certain range. The double inlet valve setting (number of turns) and the length of inertance tube are also optimized.

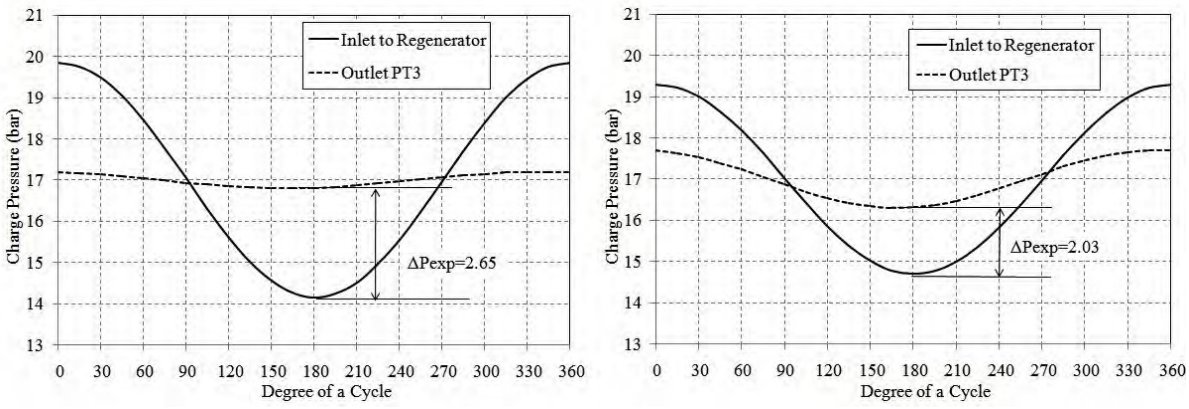
Cool down and refrigeration effect

In case-2, the two stage PTC operates at the charge pressure and frequency of 17 bar and 68 Hz respectively, while the single stage PTC operates at charge pressure and frequency of 19 bar and 50 Hz respectively. After optimizing the length of inertance tube and DI valve opening, a minimum temperature of 19.61 K is recorded at the third stage. The temperatures across the thermal bridge (TB) (Fig. 1b) are 82.27 K and 67.51 K. The temperature difference across the thermal bridge is attributed to contact resistance. As shown in Fig. 3b the PTC takes 120 minutes to reach steady state temperature with input power of 300 W, for each compressor.



a) Case-1 b) Case-2

Fig. 3. Cool down curve for three stages thermally coupled PTC.



a) Case-1 b) case-2

Fig. 4. Pressure variation for three stages thermally coupled PTC case-1.

The charge pressure of two stage PTC, which is pre-cooled by single stage PTC, is varied from 13 bar to 21 bar to measure refrigeration effect at different temperatures. A refrigeration effect of 220 mW at 30 K is obtained at the third stage for operating pressure of 17 bar with compressor input power of 300 W to each compressor.

4. Conclusion

Two different three stages thermally coupled PTC are developed and investigated experimentally. The three stages PTC with the third stage pre-cooled by two stages PTC has underperformed, due higher pressure drop in the third stage of the PTC. The single stage PTC is redesigned and used as a pre-cooling stage for the two stages PTC. The minimum temperature of 19.61 K is achieved at third stage cold end of the pulse tube for charge pressure of 17 bar and operating frequency of 68 Hz. The PTC gives the refrigeration effect of 220 mW at 30 K.

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