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Study of staging method for a 25 K two stage pulse tube cooler

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Abstract.   Staging method refers to the arrangement of regenerators and pulse tube(s) in a multi stage pulse tube cooler(PTC). This paper describes the study of two staging methods for a 25 K two stage pulse tube cooler. Staging method 1, a thermally coupled, inline staging design, was studied using SAGE and by developing an experimental PTC. A no load temperature of 40.4 K was achieved by the experimental PTC. The effect of regenerator configuration was studied by varying the regenerator length. Experimental results show a detrimental interplay of pressure drop and regenerator effectiveness resulting in higher no load temperatures. Staging method 2, consisting of thermally linked single stage 80 K PTC and two stage 25 K PTC, was studied using a SAGE model. The mass flow from the pressure wave generator is bifurcated to the PTCs; thus reducing pressure drop and regenerator ineffectiveness losses by 79% and 42% respectively. With staging method 2, a design cooling power of 1.98 W at 25 K is obtained.

1   Introduction

Pulse tube coolers operating in the 25 K region are of interest due to their potential application in high temperature superconducting systems and in neon gas recondensation [1]. Also, a novel helium recondensation system, which employs pulse tube coolers for precooling is being built in our laboratory [2]. It requires a cooling power of 14.2 W at 80 K and 1.6 W at 25 K. This paper describes the study of staging methods in a 25 K two stage pulse tube cooler (TPTC) with a goal to meet the recondensation system requirements.

Pressure Wave Generator(PWG) is crucial to the choice of the staging method. PWG used for this study was CFIC make model 2S175W (Fig. 1). It has a maximum power input of 1400 W at 50 Hz and can supply 900 W of acoustic power. Other important parameters are listed in Table 1.

2   Staging method 1

For the TPTC, a thermally coupled design, referred to as staging method 1(Fig.2), was studied initially. The advantage of this method is that the entire PV power generated by the PWG is
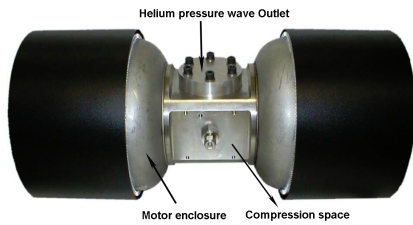
Figure 1: CFIC 2S175W Pressure Wave Generator.

Table 1: PWG motor mechanical and electric parameters

Parameter	Value
Dual opposed piston configuration	
Motor natural frequency of free decay	28.2 Hz
Piston diameter	5.715 cm
Motor coil resistance	0.63 ohm
Motor coil inductance	20 mH
Motor constant BL	35 T×m
Moving mass per motor	1.5 kg
Mechanical Stiffness	47 kN/m
Compression volume	0.165 liter
Back volume per side enclosing motors	2.1 liters

available for the generation of PV power at the cold heat exchanger.

The TPTC was designed using Sage software [3]. Entire pulse tube cooler, along with the PWG was modelled which enables the holistic design of the PTC; taking into consideration the PWG characteristics. PWG parameters were input to the Sage model. Main input parameters are the stroke and piston diameter. The design operating pressure and frequency were chosen as 25 bar and 40 Hz respectively. Components of the two stage pulse tube cooler, like Regenerator 1, 2 (Fig. 2) and the inertance tube were optimized and the optimized dimensions are shown in Table 2. For an input stroke of ±6.5 mm, the model predicts a cooling power of 0.01 W at 25 K with an input PV power of 827 W.

The pulse tube cooler was built and assembled as shown in Fig. 3. Mylar insulation was wrapped on the two stage cooler for shielding radiation. A calibrated cernox sensor was used to measure the cold heat exchanger temperature. The cooler was enclosed in a vacuum jacket maintained at 2×10^{-4} mbar. The vacuum jacket also has an inbuilt liquid nitrogen cooled thermal shield to cut-off the radiation losses.
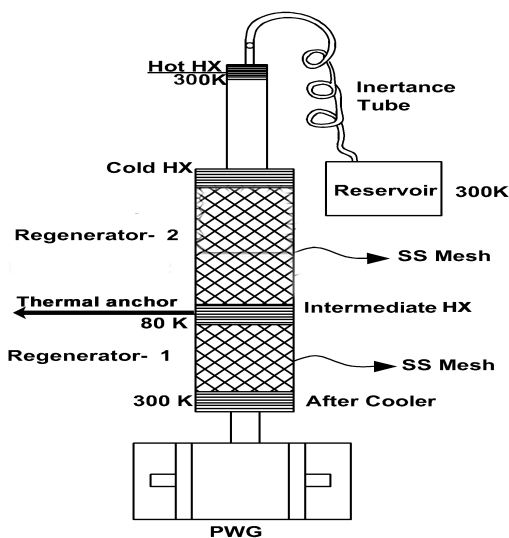

Figure 2: Schematic diagram of the staging method 1.
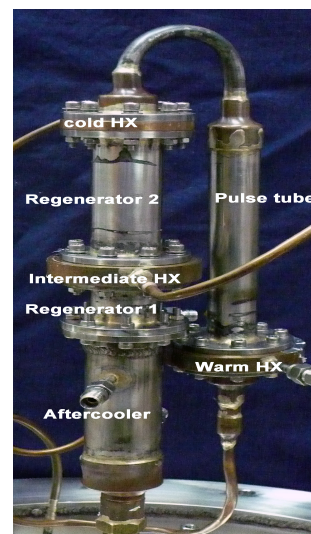

Figure 3: Two stage pulse tube cooler implementing staging method 1.

Table 2: Optimized dimensions of the pulse tube cooler obtained using Sage model.

Component	Diameter (mm)	Length (mm)	Filled with
Regenerator 1	37.7	36	# 400 SS mesh
Regenerator 2	37.7	94	# 400 SS mesh
Pulse tube	28.3	131	-
Inertance tube	4.5	2924	-

Table 3: Regenerator 2 dimensions as length was varied.

Component	Configuration		
	CF-1	CF-2	CF-3
Diameter (mm)	37.7	37.7	37.7
Length (mm)	62	94	127

2.1 Effect of Regenerator-2 length

Experiments were conducted at different lengths of the Regenerator 2 with SS #400 mesh as the regenerator material(Table 3). All other components including Regenerator 1, pulse tube and inertance tube were maintained at values given in Table 2. The cool down curves for each of the configurations CF 1–3 are given in Fig 4. No load temperature obtained with configurations CF 1–3 are 57.5, 40.4 and 44.1 K respectively.

As Regenerator 2 length is increased, no load temperature initially decreases and then eventually increases again. A longer Regenerator 2 results in increased number of transfer units (NTU) and hence higher Regenerator 2 effectiveness. Consequently, the no load temperature decreases in CF-2. But beyond a certain optimal length, the pressure drop loss increases which is manifested as a raise in the no load temperature of CF-3. It is also to be noted that the best no load temperature is 40.4 K as compared to the Sage predicted no load temperature of 25 K.

Experimental results point out the interplay of pressure drop losses and regenerator effectiveness. At optimal Regenerator 2 length, pressure drop losses are minimized but the regenerator effectiveness is low, resulting in a no load temperature of 40.4 K. If Regenerator 2 length is increased to reduce ineffectiveness, the pressure drop losses increase, resulting in a higher no load temperature. Same is the case when the regenerator material is modified by replacing a
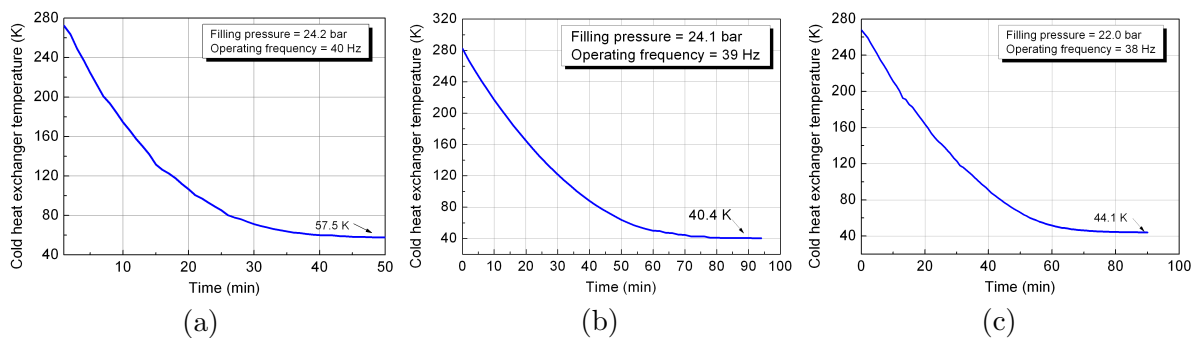

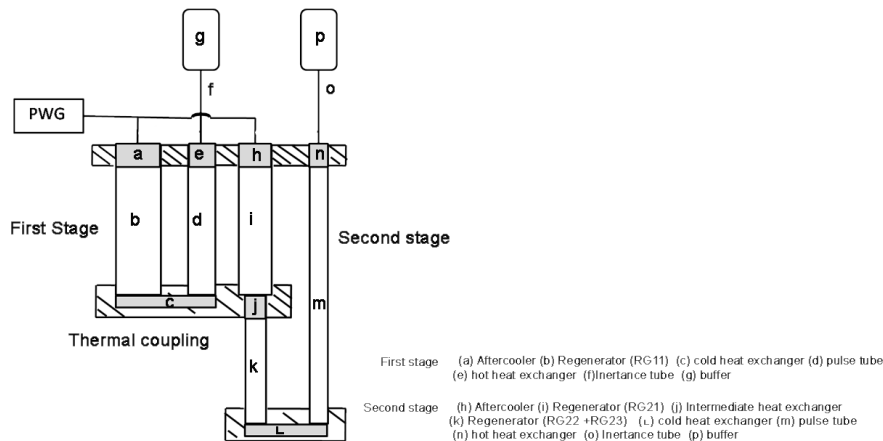Figure 4: Cool down curve for (a)CF-1 (b)CF-2 (c)CF-3

Figure 5: Schematic of the twin pulse tube cooler: staging method 2.

part of #400 with #500 meshes [4]. Thus, a regenerator length and material combination for the mass flow coming from the PWG could not be found for the staging method 1.

3   Staging method 2

An alternative staging method, referred to as staging method 2 (Fig. 5) was investigated. In staging method 2, the mass flow from the PWG is divided into two parts flowing into first and second stages. In staging method 1, the entire mass flow passes into the PTC. Thus, staging method 2 reduces the mass flow into PTC even at the entry point.

The second stage regenerator (k) was designed with both #400 meshes and #500 meshes with the latter towards the colder parts of the regenerator. The second stage pulse tube operates from the cold heat exchanger temperature to the ambient sink temperature. The dimensions of the components were optimized using Sage model and the optimized dimensions are given in Table 4. The cooling powers predicted by the Sage model are 11.52 W at 80 K and 1.98 W at 25 K for the first and second stages respectively.

4   Comparison of staging methods 1 and 2

A comparison of the staging methods is shown in Table 5. In the staging method 2, mass flow amplitude in the 80 - 25 K regenerator is reduced by 39%. Also, the friction and inefficient heat transfer losses are reduced by 79% and 42% respectively. Input PV power required is 74% lower for the twin cooler. Thus staging method 2 produces more cooling power at 25 K than staging method 1. The design cooling powers of TPTC using staging method 2 are sufficient to meet the 25 K cooling requirement of the recondensation system.

5   Conclusions

Two staging methods were studied for building a pulse tube cooler capable of reaching 25 K. It was found that staging method 2 is advantageous compared to staging method 1 when employing the particular pressure wave generator. Choice of staging method is crucial for making the best use of the PV power from the pressure wave generator.

Table 4: Dimensions of twin pulse tube cooler components obtained using sage model. The component labels in brackets refer to that indicated in Fig. 5

Component	Diameter mm	Length mm	Component	Diameter mm	Length mm
First Stage			**Second Stage**		
Regenerator (b) with #400 meshes	37.7	60	Regenerator (i) with #400 meshes	37.7	60
Pulse tube (d)	24.7	60	Regenerator (k) with #400 meshes	30.8	32
Inertance tube (f)	4.5	4000			
			Regenerator (k) with #500 meshes	30.8	15
Aftercooler (a)	37.7	10			
Cold heat exchanger (c)	37.7	10	Pulse tube (m)	24.7	88
Hot heat exchanger (e)	24.7	10	Inertance tube (o)	4.5	1537
Buffer (g)	250 cm^3		Aftercooler (h)	37.7	10
Buffer (p)	250 cm^3		Intermediate heat exchanger (j)	37.7	10
			Cold heat exchanger (L)	30.8	10
			Hot heat exchanger (n)	24.7	10

Table 5: Comparison of the staging methods 1,2 based on Sage model predictions.

	Staging method-1	Staging method-2
Regenerator-2 operating range	80 - 25 K	80 - 25 K
Mass flow amplitude	15.4 g/s	9.3 g/s
Energy loss due to friction	19.3 W	3.9 W
Energy loss due to insufficient heat transfer	7.6 W	4.4 W
Hot heat exchanger temperature	300 K	300 K
Design cooling power at 25 K	0.01	1.98 W
Input PV power at aftercooler	827 W	211 W

6   Acknowledgements

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