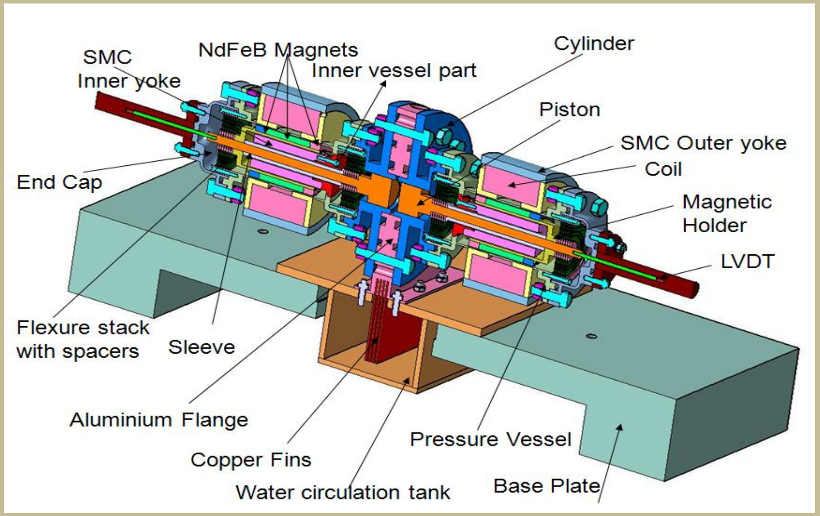
Improved performance of an indigenous Stirling type pulse tube cooler and pressure wave generator

Kranthi Kumar J.[1] , Jacob S.[1], Karunanithi R.[1], Narasimham G.S.V.L.[2], Damu C.[1], Praveen T.[1], Samir M.[1]

[1]Centre for Cryogenic Technology, Indian Institute of Science.
[2]Mechanical Engineering Department, Indian Institute of Science.

Introduction – Background

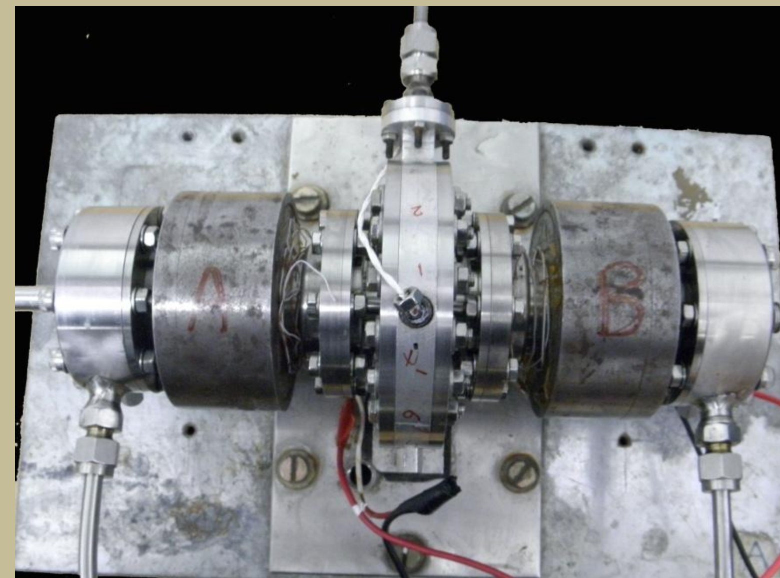
- Indigenous program initiated at Indian Institute of Science, Bangalore to develop pressure wave generator (PWG) and pulse tube cooler technology, 5 years back.



1. Dual opposed piston configuration.
2. Moving magnet technology-Ring magnet, Nd-Fe-B- main magnets & side magnets.
3. Material of construction- Largely Ti-6Al 4V and Al 6061.
4. Spring steel spiral flexure
5. Soft Magnetic composite Yokes
6. Max Design gas fill pressure = 30 bar.
7. Stroke - ± 2.8mm
8. Swept volume – 2 cc
9. Operating frequency range = 53 – 100 Hz.
10. Size of PWG – Diameter 80mm X Length 250 mm.
11. Weight of PWG – 3.2 kg

Optimization of the PWG

- PWG improved by optimizing
  - Piston diameter
  - Maximum piston stroke
  - Seal gap
  - Moving mass
  - Total effective back volume



- Resulted in reduced pressure and flow losses
- Experiments with a readily available pulse tube achieved a no load temperature of 130 K (reported in CEC 2013)
- Low performance is due to acoustic mismatch

Design of an acoustically matched pulse tube cooler

- Designed using Sage software
- Operating frequency is the combined resonance frequency of PWG-PTC : estimated to be 79 Hz using

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{K_{front} + K_{back} + K_{flexure} + K_{magnetic}}{m}}$$

- Flexure, magnetic stiffness input to the Sage model
- Imposed constraints : Stroke limit : ± 2.5 mm per motor , Current limit: 3.5 A per motor
- Regenerator, pulse tube and inertance tube diameters chosen from previous experimental results
- Optimized the lengths of regenerator, pulse tube and the inertance tubes

New pulse tube cooler

Component	Diameter (mm)	Length (mm)	Mesh (#)
Regenerator	9.5	68	SS 400
Pulse tube	7	78	NA
Inertance tube 1	2	659	NA
Inertance tube 2	3	2155	NA
Aftercooler	9..5	10	Cu 100
Cold heat exchanger	7	10	Cu 100
Hot heat exchanger	7	10	Cu 100

From Sage analysis

Filling Pressure = 25 bar
Predicted cooling power = 0.4575 W @80K
No load temperature = 63 K
Best operating frequency = 79 Hz

Pressure Wave Generator:

Total stroke = 5 mm
Total Current = 4.288 Amps
PV power = 28.72 W
Total Input Power =
PV power + I^2R + Pressure &flow loss (experimental data) = (28.72+9.19+17) = 54.9 W

Pressure amplitudes

PWG = 1.709 bar
regenerator hot end = 1.663 bar
Regenerator cold end = 1.198 bar
Hot heat exchanger = 1.174 bar
Mass flow amplitude at Aftercooler =0.57 g/s
PV power at cold end = 2.208 W

Experimental plan with the designed cooler

- Regenerator and pulse tube fabricated out of Titanium
  - wall thickness : 0.30 mm
- Regenerator
  - A critical component
  - Effectiveness influenced by length, wire diameter and porosity
- Experimented with different regenerator stacking
- Stacking configuration : based on thermal penetration depth

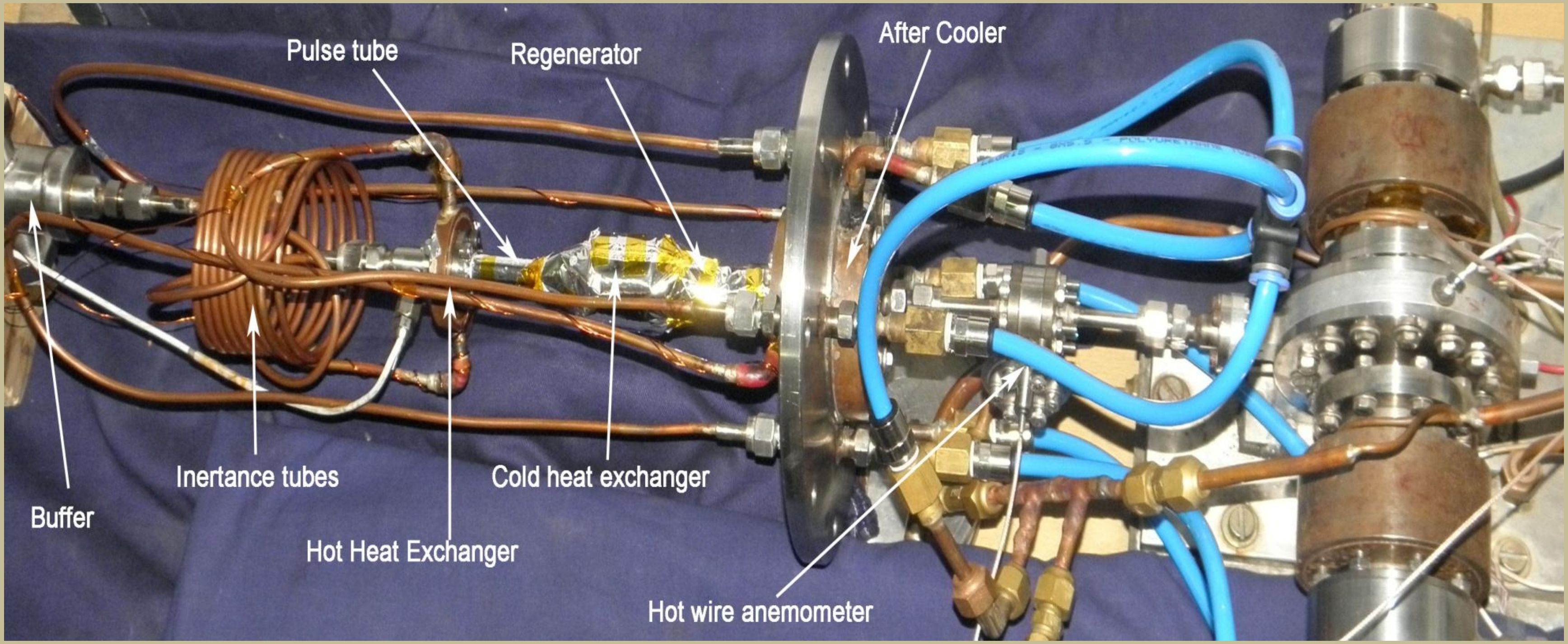
RG -1

Component	Filling length (mm)
Regenerator	
# 400 mesh	68

RG -2

Component	Filling length (mm)
Regenerator	
#250 mesh	48
#325 mesh	5
#400 mesh	15
Total	68

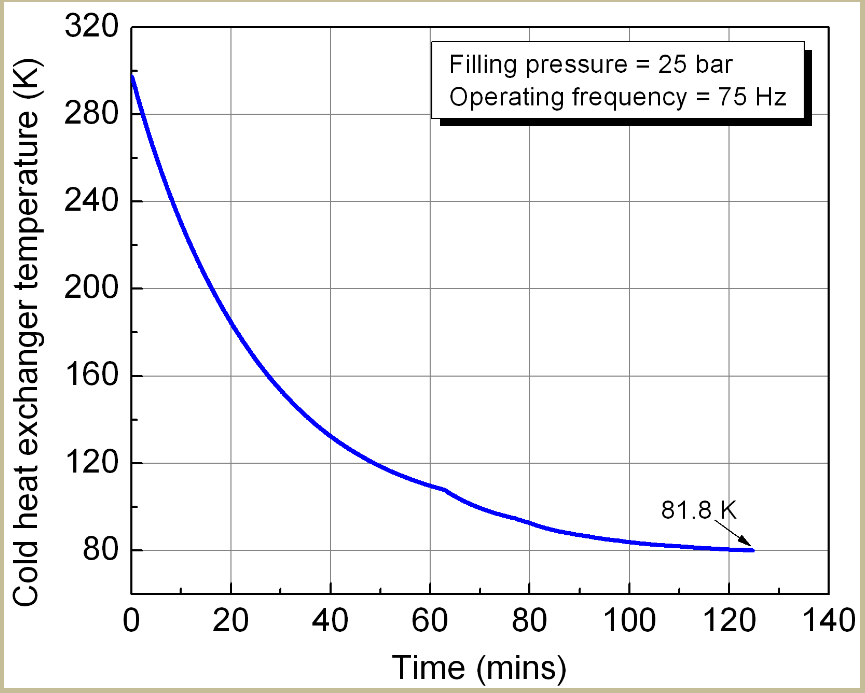
Pulse tube cooler in assembled condition



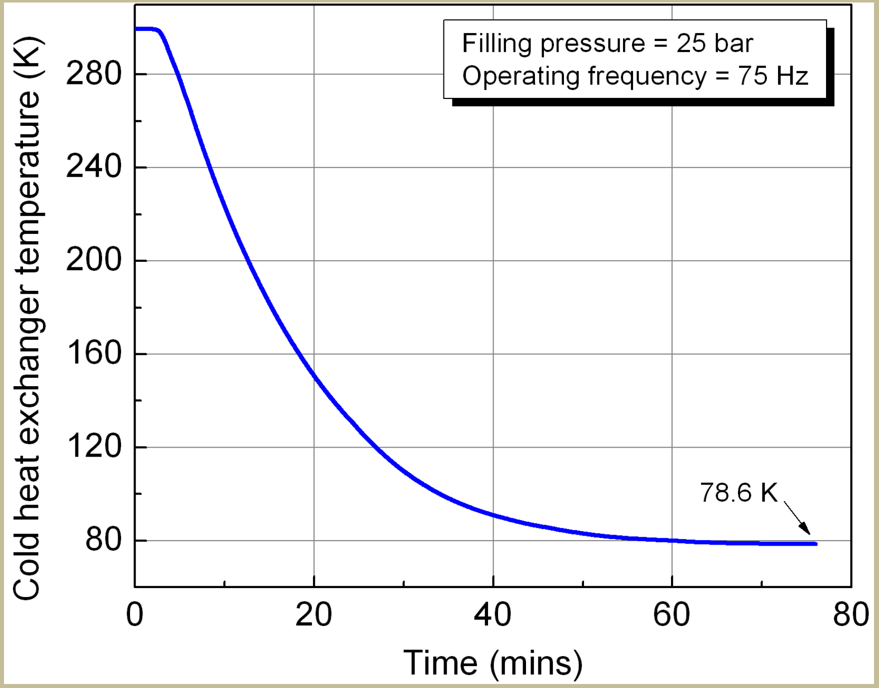
Evacuated continuously to a vacuum of 5E-4 mbar

Experimental Results at 25 bar

With RG -1



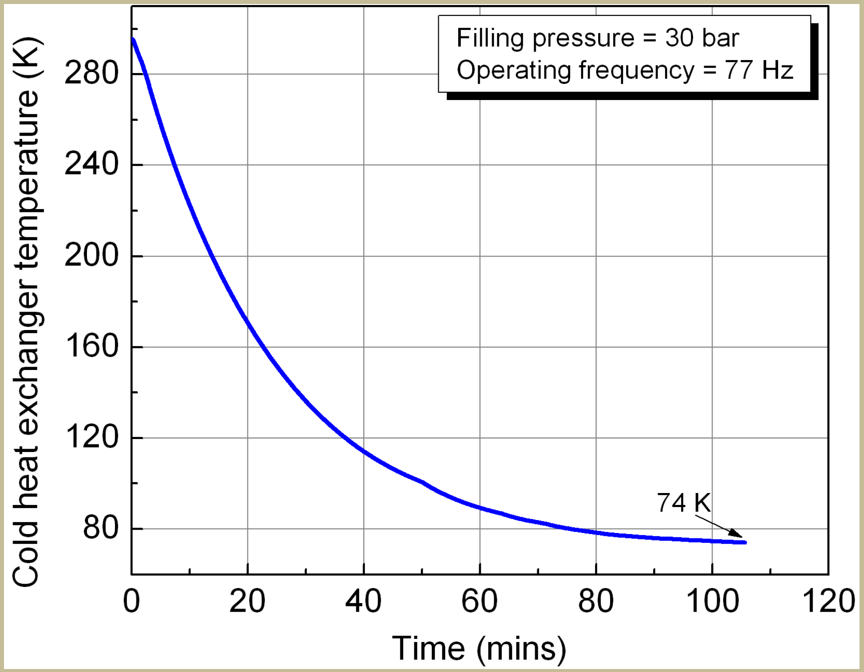
With RG -2



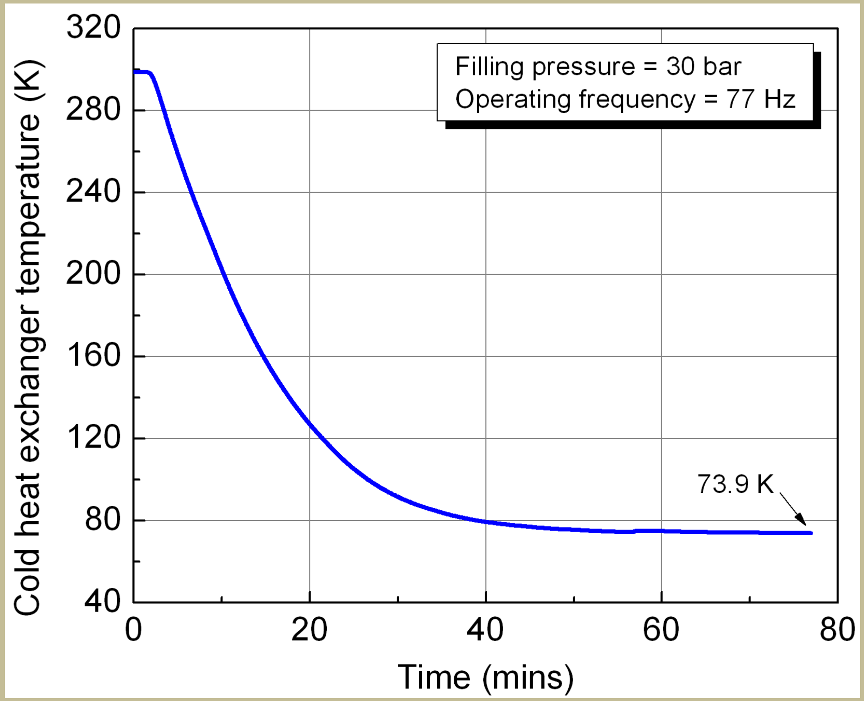
- No load temperature of 78.6 K is achieved - indicates a small cooling power at 80 K
- Difference in cool down times
  - RG – 1: Stroke increased progressively
  - RG – 2: Full stroke given initially

Experimental Results at 30 bar

With RG -1



With RG -2



- A no load temperature 74 K is achieved in both the experiments.
- The estimated cooling power at 80 K is 0.22 W (using Sage)
- Below the design target of 0.5 W at 80 K

Experimental Observations during cooler runs

Regenerator →	RG-1	Sage RG-1	RG-2	RG-1	RG-2
Filling Pressure (bar)	25	25	25	30	30
Frequency (Hz)	75	79	75	77	77
Total Stroke amplitude (mm)	4.6	5	5	4.4	5.1
Current (A)	4.69	4.29	5.24	4.81	6
Power (W)	57.1	54.9	63.7	58.8	82
Mass flow amplitude to Aftercooler (From Hot wire anemometer measurements)	0.6	0.57	-	0.65	-
Pressure amplitude in PWG (bar)	1.79	1.71	2.06	1.82	2.34
Pressure amplitude at Hot Heat Exchanger (bar)	0.69	1.17	0.34	0.76	0.48
No load temperature (K)	81.8	63	79	74	73.9

- More stroke achieved in experiments with stacked regenerator RG-2
- Resulted in higher pressure amplitude in the PWG
  - higher by 15% and 28.5% at 25 and 30 bar respectively
- Did not result in higher pressure amplitude in the hot heat exchanger
  - Lower by 50.7% and 36.8% at 25 and 30 bar respectively
- Contrary to expectations: more experiments are required

Analysis of experimental results : no load temperature

- Maytal and Pfotenhauer (2013) discuss the lowest attainable stable temperature of cryocooling

  (Miniature Joule-Thomson cryocooling: principles and practice)

$$T_{noload} = function(NTU, \eta, Pr)$$

NTU : number of transfer units of the regenerator
η : effectiveness of heat exchange in the regenerator
Pr : ratio of pressure high to pressure low

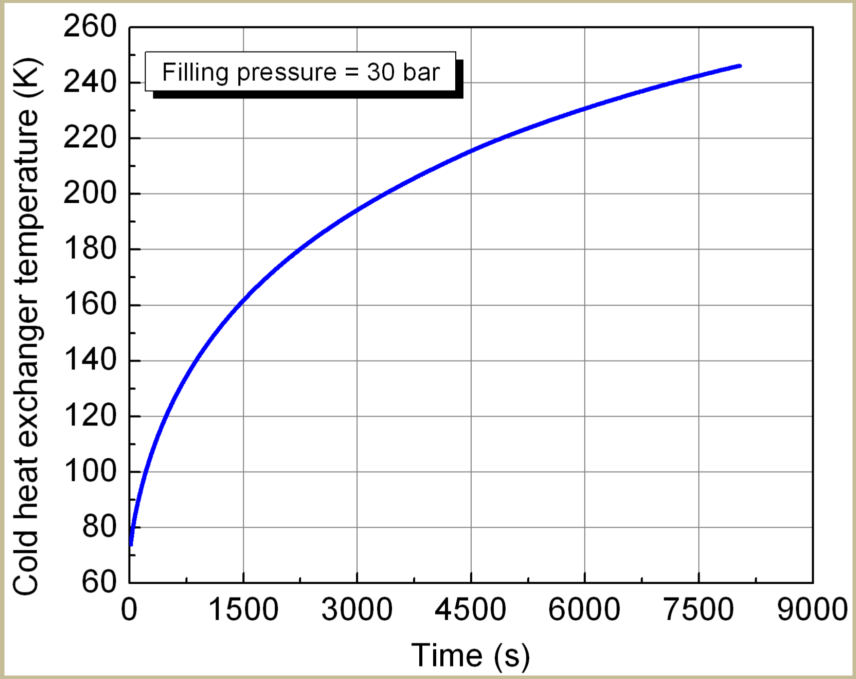
- In experiments with RG-1 to RG-2 at 25 bar
  - No load temperature changes from 81.8 to 79 K : improvement of only 2.8 K
  - Pressure ratio *Pr* is almost same: changes by only 3%
  - RG-2 and RG-1 have the same combined effect of NTU and η
- Similar equality is seen at 30 bar where the no load temperature remains the same at 74 K

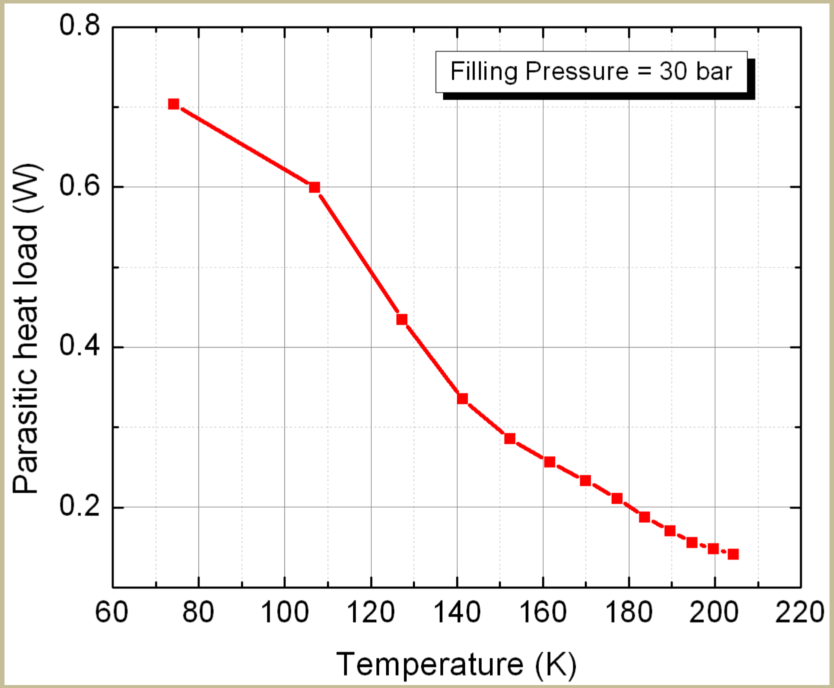
Analysis of experimental results: power

Regenerator	RG-1	Sage RG1	RG-2	RG-1	RG-2
Filling Pressure (bar)	25	25	30	25	30
No load temperature (K)	81.8	63	79	74	73.9
Current (A)	4.69	4.29	5.24	4.81	6
Power (W)	57.1	54.9	63.7	58.8	82
Copper loss (W)	11.0	9.2	13.7	11.6	18.0
Pressure Loss + Flow Loss (W)	15.5	17	16	21	22
Net PV Power input (W)	30.6	28.72	34.0	26.2	42.0

- RG-1 efficiency increases with filling pressure
  - Able to produce 74 K with 26.2 W input power
- More PV power is delivered in experiments with RG-2 compared to RG-1
- RG-2 consumes more PV power to produce the same no load temperature of 74 K

Estimation of parasitic heat load





- The PWG was switched off and the warmup of cold heat exchanger was measured

$$\text{Parasitic heat load} = m_{CHX} * C_{copper} * \frac{dT_{CHX}}{dt}$$

Analysis of parasitic heat load

- Experimental Parasitic heat load from warmup data at 80 K is 0.68 W
- Estimated load due to thermal conduction of regenerator wall is 0.47 W
- Estimated load due to thermal conduction of the pulse tube wall is 0.30 W
- Total heat load due to wall conduction is 0.77 W and is a little higher than the experimental parasitic load due to possible heat leaks
- Wall conduction is the major factor contributing to parasitic heat load

Conclusions

- A pulse tube cooler which is acoustically matched to the indigenous pressure wave generator was designed, fabricated and tested
- Different regenerator filling patterns were experimentally tested
- In present experiments, regenerator with #400 mesh at 30 bar filling pressure performed better with more energy efficiency
- A no load temperature of 74 K was achieved with input power of 59 W corresponding to a cooling power of 0.22 W at 80 K

Conclusions

- Parasitic heat load to the cooler was estimated to be 0.68 W primarily by heat conduction through the regenerator and pulse tube wall
- By reducing the wall thickness from 0.30 mm to 0.15 mm, the parasitic loads can be reduced by 50% and the design target of 0.5W at 80 K can be achieved

Thank you