Development of a helium recondensing cryostat

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Abstract. The present paper illustrates a case study in the progress of ongoing research work to develope a 100 litre Helium cryostat with in-situ recondensing facility. The cryostat with a cryocooler sock comprises 46 components assembled in an optimal sequence. Cryostat development involved thermal load estimation, mechanical design, fabrication of components and sub-assemblies. The cryostat deploys a two stage Gifford McMahon cryocooler with appropriate cooling capacities available on 1st and 2ndstage.The thermal load due to the cryostat assembly is estimated as 34 W and 300 mW for 1st and 2ndstage of the cryocooler respectively. Experimental trials are conducted for testing of the cryostat with recondensing cryocooler. The first no load trial in vacuum produced unsatisfactory results. Appropriate modifications are carried out in the assembly which resulted in no load temperatures of 51.95 K on 1ststage and 3.43 K on 2ndstage. At a heater load of 0.448 W, the 2ndstage stabilized at 4.21 K while 1ststage temperature stabilized at 52.47 K without any heater load on 1ststage. Temperature increased from 51.95 K to 52.47 K for 1ststage showing 0.448 W cooling capacity available at 2ndstage for recondensation at 1 bar pressure. The paper highlights these modifications towards successful development of the Helium recondensing cryostat.

1. Introduction

Helium is a unique cryogenic resource with normal boiling point of 4.2 K at pressure of 1 atm. Global consumption of Helium is increasing due to its numerous cryogenic applications. Conventional cryostats are being widely used in cryogenic applications and need periodic refilling of liquid Helium. It results in frequent disruption in smooth system operation and also heavy loss of liquid Helium from the supply Dewar. As such, these cryostats require a Helium liquefaction plant with a Helium recovery system in the vicinity, involving huge infrastructure and associated cost. In this scenario, technological efforts for conservation of Helium become imperative. The present work is a step towards conservation of liquid Helium with the objective to develope a demonstration set-up of a Helium recondensing cryostat having 100 litre of liquid Helium holding capacity with a normal permissible boil-off rate of about 1% per day.

2. Mechanical and thermal design

The present Helium recondensing cryostat assembly comprised 46 components designed, fabricated and assembled in an optimal sequence to form three main assemblies namely, the cryovessel, sock and cryocooler assembly. Integration of these main assemblies resulted to form the present Helium recondensing cryostat assembly.

2.1. Cryovessel Assembly

The cryovessel assembly consisted of sub-assemblies of inner vessel, support member, radiation shield, outer vessel and neck. The inner vessel was designed for an internal pressure of 6 bar and 100 litre liquid Helium storage capacity with length to inside diameter ratio (l/d) of 0.9 and 6% of liquid volume as ullage volume. Mechanical design of shell and torispherical heads for inner and outer vessel was carried out using standard formulae as per ASME Code, Section VIII, Division I [1]. The inner vessel shell was designed as 4 mm thick, SS-304 cylinder of φ496 mm inside diameter (ID) with 4 mm thick SS-304 torispherical top and bottom heads. Perforated radiation shield of 1.5 mm thick Electrolytic Tough Pitch (ETP) Copper was designed with 1.5 mm thick ETP Copper torispherical top and bottom heads. The outer vessel shell was designed as 6 mm thick SS-304 cylinder of φ638 mm ID with 6 mm thick SS-304 torispherical top and bottom heads. Multilayer Insulation (MLI) of 0.006 mm Aluminum foil with 0.15 mm fiberglass paper insulation having layer density of 20 layers/cm and apparent thermal conductivity, k_a=37 μW/m.K with 40 layers was applied between inner and outer vessel and also evacuating this space [2],[3]. Figure 1 shows schematic diagram of support member sub-assembly, consisting of SS-304 bush-1 and 2 (indicated as 1 and 2) and SS-304 connecting ring (indicated as 4 and 4A) with support rod-1(indicated as 2A and 2B) and support rod-2 (indicated as 2C and 2D) of fiberglass epoxy cryogenic insulation G-10 CR. Design of support member was carried out using standard formulae and criterion for ensuring its strength against failure due to compression, shear and buckling loads [4],[5].

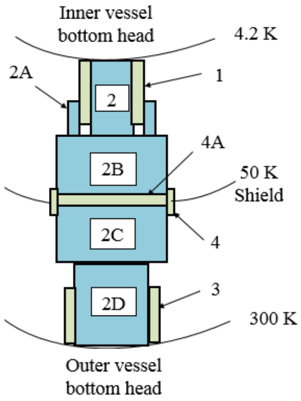


Figure 1. Schematic diagram of support member.

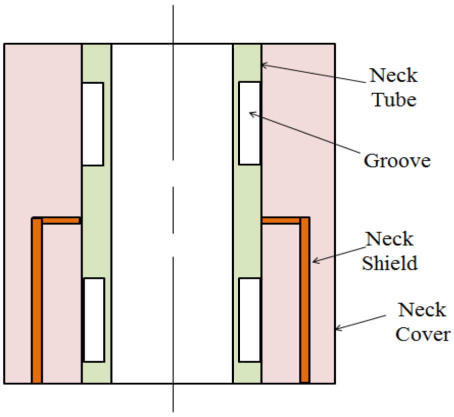


Figure 2. Schematic diagram of neck sub-assembly.

Neck tube was designed as a standard 2.11 mm thick SS-304 pipe of φ42.5 mm outside diameter (OD). Two grooves were machined symmetrically on neck tube, resulting in neck tube wall thickness of 0.7 mm for its length of grooved portion. Schematic diagram of neck sub-assembly is shown in figure 2. Perforated neck shield was designed as 1.5 mm thick ETP Copper. The neck cover was designed as a standard 2.11 mm thick SS-304 pipe of φ114.3 mm OD. 25 layers of MLI were provided in the annular space between neck tube and neck shield as well as between neck shield and neck cover. Neck tube and neck cover design was confirmed to be safe using collapsing pressure criterion as per ASME Code [1].

2.2. Sock assembly

The sock assembly enclosed various components for enabling smooth insertion and proper positioning of the cryocooler inside the cryostat to ensure “in-situ” recondensation of boil-off Helium vapour. The

1ststage cryostat flange of ETP Copper was designed with H6 tolerance on its taper ID. Thermal linkage between 1ststage cryostat flange and radiation shield was provided by 16 sets of 80 mm long, 32 x 30 x 0.2 mm braided Copper wires, each fitted with two ETP Copper lugs. The radiation shield was brazed to neck tube to ensure thermal linkage of neck tube to 1ststage of the cryocooler. Design of sock assembly was confirmed to be safe using collapsing pressure crierion as per ASME Code [1]. Design of radiation shield in cryovessel, neck and sock was confirmed to be safe using buckling criteron [4],[5].

2.3. Cryocooler assembly

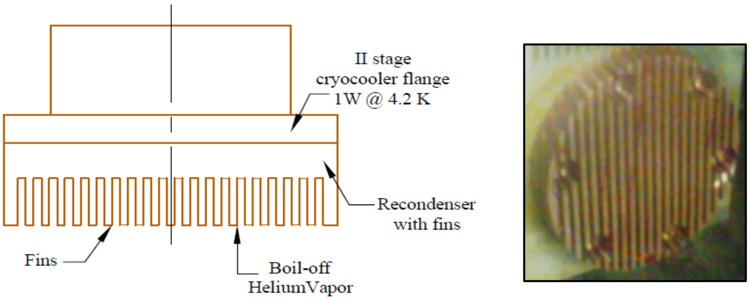
The cryostat deployed a commercially available SHI model RDK-408D2, two stage GM cryocooler having specified refrigerating capacity of 40 W at 43 K for 1ststage and 1 W at 4.2 K for 2ndstage [6]. The components namely, adapter flange at 300 K, 1ststage adapter flange and 2ndstage re-condenser were specially designed, fabricated and fastened to the respective integral flanges of the cryocooler.

2.3.1. 1ststage adapter flange. This flange made of Oxygen free high conductivty (OFHC) Copper with h6 tolerance on its taper OD is mounted on integral flange of the cryocooler at 1ststage. Precison location rotational sliding fit with H6 tolerance at the mating taper faces of both the 1ststage flanges ensured perfect alignment with minimum contact thermal resistance without use of Indium between them. This would result in minimum loss during transfer of cooling effect generated at 1ststage of the cryocooler to radiation shield through linkage of 1ststage flanges and braided Copper wires. Photographs of 1ststage adapter flange, 1ststage cryostat flange and assembly of both the 1ststage flanges are shown in figure 3.


(a) (b) (c)

Figure 3. Photographs of (a) 1ststage adapter flange with insert, (b) 1ststage cryostat flange, (c) Assembly of both 1ststage flanges.

2.3.2. 2ndstage Re-condenser. The re-condenser made of OFHC Copper is mechanically coupled to integral flange of the cryocooler at 2ndstage to maintain the surface of re-condenser at a temperature slightly lower than boiling point of liquid Helium at working pressure of 1 bar. This would ensure "in-situ" re-condensation of boil-off Helium vapour in the cryostat. Analysis resulted in design of Helium re-condenser with 19 straight rectangular integral fins, each of 1.5 mm thickness and 10 mm height with a gap of 1.5 mm between the two fins. Schematic diagram and photograph of 2ndstage re-condenser are shown in figure 4.



(a) (b)

Figure 4. (a) Schematic diagram and (b) Photograph of 2ndstage re-condenser.

The fins were cut on an inclined blank of varying thickness of 20.7 mm at one edge and 17.5 mm on the diametrically opposite edge to ensure that condensed liquid will collate at one end of fin and drop from there [7]. Minimum theoretical gap between two Fins (G_{min}) was estimated to be 0.287 mm to ensure that choked flow would be avoided for Helium vapour condensing on this surface. Total length and area of finned surface was calculated as 2053.54 mm and 0.02 m^2 respectively. Values of condensation heat transfer co-efficient h, fin effiency η and fin effectiveness ϵ were estimated as 1385 $W/m^2.K$, 80.96% and 10.34 respectively [7]. Figure 5 shows photograph of cryocooler assembly with 1ststage adapter flange and 2ndstage re-condenser mounted on respective integral flanges at 1st and 2ndstage of cryocooler.

Figure 5. Photograph of 1ststage adapter flange and 2ndstage re-condenser mounted on 1st and 2ndstage cryocooler flanges.

3. Performance testing of GM cryocooler before mounting on recondensing cryostat

Continuous trials were separatetly conducted on SHI two stage GM Cryocooler in a specially fabricated vacuum jacket for evaluation of its performance. Heat loads of 40 W at 40.3 K and 1 W at 4.02 K were obtained respectiviely at the 1st and 2ndstage against its technical specifications of 40 W at 43 K and 1 W at 4.2 K for 1st and 2ndstage respectively [6]. In experimental runs, 1ststage heater load was varied as 0 W, 1 W, 4 W, 8W, 15W and 20 W and 2ndstage heater load was varied as 0 W, 20 W, 40 W and 60 W using a D.C. power supply of maximum capacity of 60 W. Experimental results of temperatures at 2ndstage vs. 1ststage of the cryocooler obtained by applying various electrical heater loads to both the stages were plotted and compared with thermal load map specified by SHI [6]. Performance of the cryocooler was better than the technical specifications by SHI which confirmed its ability for use in 100 litre Helium recondensing cryostat. Comparison of thermal load map of the cryocooler plotted using technical specifictions and results of experimental trials is shown in figure 6.

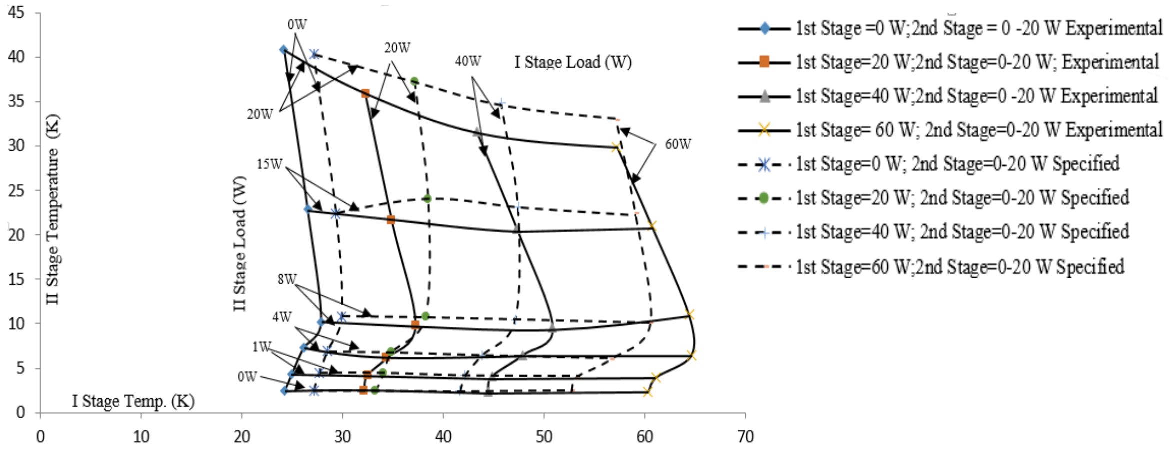
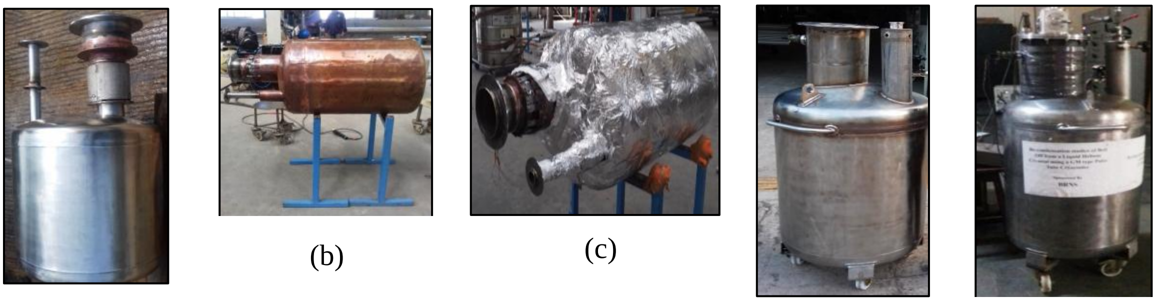


Figure 6. Thermal load map of the cryocooler for SHI specifications [6] and experimnental results.

4.Fabrication

Various manufacturing processes for the present recondensing cryostat included forming, machining, joining and MLI application as per the design and functional requirement. Quality conformance tests of pneumatic and hydrostatic pressure tests and mass spectroscopy leak detection (MSLD) test using Helium gas were conducted as per ASME Code [1] with satisfactory results.Photographs of stages of fabrication of the cryostat assembly are shown in figure 7.



(a) (b) (c) (d) (e)

Figure 7. Photographs of stages of fabrication of Helium recondensing cryostat assembly (a) Inner vessel, (b) Integration of inner vessel with middle Copper shield, (c) Application of MLI on shield assembly, (d) Integration with outer vessel, (e) The cryocooler mounted on recondensing cryostat.

5. GM cryocooler testing in cryostat

5.1. Problems aligning the cryocooler within the cryostat

Due to errors of fabrication at the works of fabricator, a few problems arose during assembly of the cryocooler in sock assembly of the cryostat. Figure 8 shows schematic diagram of sock assembly with problems in assembly of the cryocooler which required modifications.

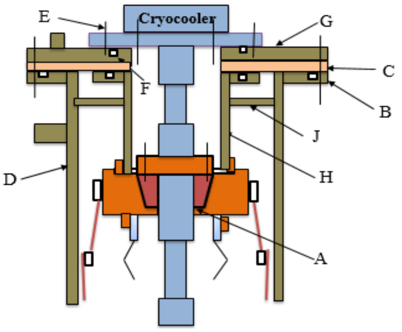


Figure 8. Schematic diagram of sock assembly with problems in assembly of the cryocooler.

Reasons identified for problems in assembly of the cryocooler in sock assembly and corrective measures taken to resolve them are discussed below.

- Lapping at flat face A of 1ststage cryostat flange was not carried out at fabricator's end. This resulted in waviness at face A. Hence bottom face of 1ststage adapter flange was not resting perfectly with mating face A of 1ststage cryostat flange, leaving a gap and creating a large heat transfer resistance between the two mating surfaces. A special tool was made in-house to polish face A and make it smooth, ensuring perfect contactt of both the 1ststage flanges.
- With top face of intermediate flange C and bottom face of 300 K adapter flange G, matching at one edge, a gap varying upto maximum of 3 mm was observed between the two faces at diametrically opposite edge. This was due to uneven level of outer sock cylinder top flange, B due to its deformation during its welding with outer sock cylnder D. Intermeidate Flange C (7 mm thick) was discarded from sock assembly. Weld between outer sock cylinder D and its top flange B was removed. A taper cylindrical packing ring φ236.7 mm ID x φ247.1 mm OD with thickness of 7 mm at one edge and 4 mm on the diametrically opposite edge was fused with outer sock cylinder D.

- Eight M-5 x 9 Tapped holes E were blinded by 1 mm from bottom and O-Ring F in 300 K Adapter Flange G was changed from φ3.5 mm to φ5 mm. Thus, possibility of any leakage past O-Ring F was eliminated.

5.1.1. First trial of the cryocooler in the cryostat. The first trial of the crycooler in the cryostat ended up with heavy condensation of ambient water vapour on the outer surface of outer sock cylinder D. Unsatisfactory results of high temperatures of 82.60 K and 6.47 K for 1st and 2ndstage respectively at no electrical heater load were obtained. The steps for quality performance of the cryostat are concluded below.

- High thickness of vacuum retention plate, J (7 mm at inner and outer end portions for circumferrential weld and 4 mm between the end portions) caused high radial conduction heat transfer from ambient to 1ststage resulted in high temperatures as above.
- Minimized radial solid conduction from ambient to 1ststage by provision of φ3 mm slot in 4 mm thickness of vacuum retention plate J (Only about 3 mm wide solid portions at three locations 120° apart was retained) and use of φ5 mm neoprene rubber O-ring and vacuum clay in the slot. Inner vessel volume and insulation space both were evacuated to a high vacumm of the order of less than 10^{-6} mbar.Temperatures of around 51 K and 5–6 K were obtained at the 1st and 2ndstage on operating the cryocooler again.
- Cracking of vacuum clay had and loss of vacuum on insulation side was observed due to drying of vacuum clay at very low temperature and under high vacuum. Applied araldite as sealant around O-ring instead of vacuum clay.
- Continuous trial of the cryocooler was conducted for 8 days. Cooldown resulted in steady tempertaures of 50.75 K and 3.80 K at 1st and 2ndstage respectively at no electrical heater load. Satisfactory results of 51.33 K at 1ststage and 0.336 W at 4.21 K for 2ndstage were obtained on applying electrical heaterload to 2ndstage only.
- Vacuum loss at low temperatures during LN_2 purging was observed in the cryostat before going ahead for LHe test of the cryostat. This was due to formation of pores and cracking of araldite on exposure to extremely low temperatures for long duration during first trial of cryocooler. Neoprene rubber O-ring from slot of vacuum retention plate was removed.

5.1.2. Modified sock assembly. A 0.2 mm thick SS-304 shim was soldered between outer sock cylinder top flange B and trimmed flanges of inner sock cylinder H. Figure 9 shows schematic diagram of modified sock assecmbly with provision of 0.2 mm thick shim. Photograph of sock assembly with 0.2 mm thick SS-304 shim soldered for vacuum retention in the cryostat is shown in figure 10.

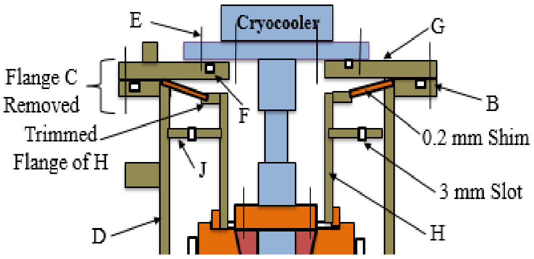


Figure 9. Schematic diagram of modified sock assembly with 0.2 mm thick SS-304 shim.

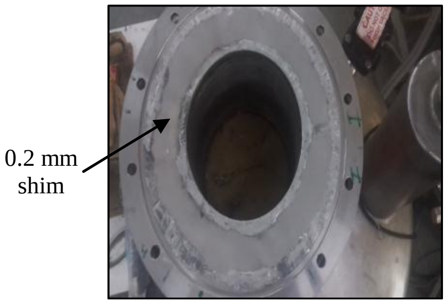


Figure 10. Photograph of 0.2 mm thick SS-304 shim soldered in sock assembly.

Analysis of solid conduction thermal load of sock assembly for 1ststage of cryocooler was carried out for its mechanical design before and after modifications. Refer figure 8 and 9 for schematic diagram of sock assembly before and after modifications. The effect of these modifications is shown in table 1. Thus the undesired effect of high radial conduction heat in-leak due to thick vacuum retention plate J in sock assembly was nullified by providing a 0.2 mm shim for vacuum retention in the cryostat.

Table 1. Effect of rectifications in design of sock assembly on its themal load for 1ststage.

Arrangement in sock assembly	Conduction heat load (W)		
	Radial	Axial	Total
1. Thick vacuum retention plate J only.	66.63	22.62	89.25
2. Vacuum retention plate with φ3 mm slot, φ 5 O-ring and sealant.	16.06^a	22.40	38.46
3.Vacuum retention plate with φ3mm slot withoutO-ring.0.2 mm thick SS-304 Vacuum retention shim soldered.	5.35^b	22.40	27.75

[a] Includes 0.967 W due to vacuum retention plate.

[b] Includes 0.967 W and 4.38 W due to vacuum retention plate and vacuum retention shim respectively.

5.3. Cryostat Assembly and thermal load estimation

Thermal load due cryostat assembly after modifications, as shown in figure 7, part (e) , on 1ststage and 2ndstage of cryocooler was estimated using standard formuale for heat transfer [2],[5]. The conduction heat load due to leadwires of the cartridge heater, Silicon diode and Pt100 at the 1ststage and the cartridge heatrer, Silicon diode at the 2ndstage was estimated. Results of thermal load estimation due to the cryostst assembly after modifications is shown in table2.

Table 2. Results of themal load estimation due to cryostat assembly (after modification).

Thermal Load (W)	Cryovessel		Neck		Sock	
Stage of the cryocooler:	1st	2nd	1st	2nd	1st	2nd
1.Solid Conduction	2.73	0.076	1.74	0.08	27.75	0.045
2.Radiation	0.67	2.23 x10^{-4}	0.119	2.17 x10^{-5}	0.337	0.056
3.Residual Gas Conduction	0.33	0.038	0.011	2.86 x10^{-4}	0.039	1.5 x10^{-3}
Total (1+2+3)	3.73	0.114	1.87	0.08	28.13	0.103
Stage of the cryocooler:	1st			2nd		
Thermal Load due to cryovessel, sock and neck on the cryocooler	33.72			0.298		
Conduction load due to leadwires	6.67 x 10^{-3}			4.98 x 10^{-3}		
Total Thermal Load	33.73			0.303		
Cryocooler Specifications	40 W at 43 K			1 W at 4.2 K		
Cryocooler Performance (our test)	0 W at 52.47 K			0.448 W at 4.21K		

6. Results and discussions

The demonstration set-up of a Helium recondensing cryostat was developed and experimental trials were conducted for testing of the cryostat in vacuum.The first trial produced unsatisfactory results of 82.60 K and 6.47 K for 1st and 2ndstage respectively at no electrical heater load.The modifications of nullifying the effect of thick vacuum retention plate by using 0.2 mm thick shim for vacuum retention in sock assembly resulted in significant reduction of solid conduction heat load of sock assembly on 1ststage of cryocooler from 89.25 W to 27.75 W as presented in table 1. Thermal load due to the cryostat assembly was estimated as 33.73 W and 0.303 W for 1st and 2ndstage of the cryocooler respectively as shown in table 2. The second trial of the recondensing cryostat with the cryocoooler inserted in it was conducted after the modifications. Almost steady state temperatures of 51.95 K and 3.43 K for 1ststage and 2ndstage respectively were obtained after cooldown. Satisfactory results of 0.448 W at 4.21 K for 2ndstage and 52.47 K with no electrical heater load at 1ststage were produced in the second trial.

Results of this successful trial are shown in figure 11 and 12.

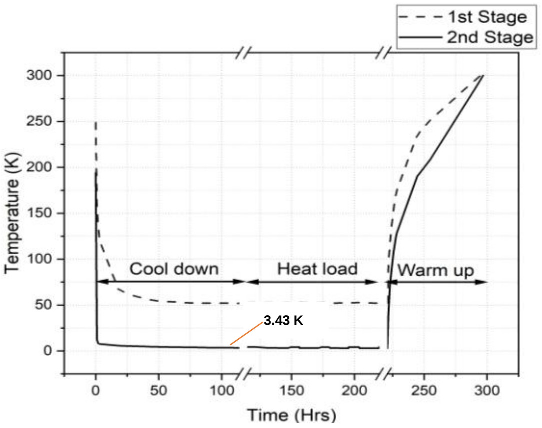


Figure 11. Cool down curve of Helium recondensing cryostat performance test in vacuum.

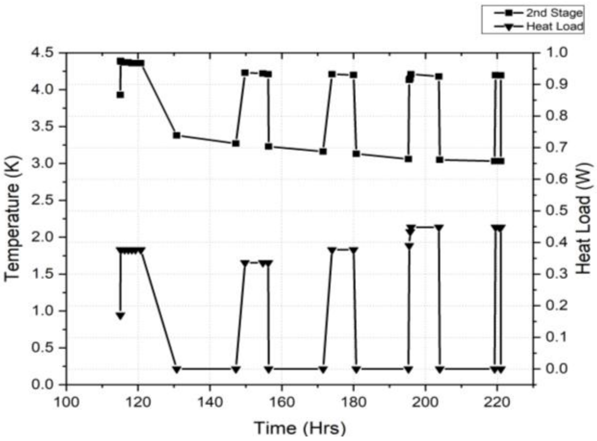


Figure 12. 2ndstage temperatures and applied electrical heater load for cryostat performance test in vacuum.

7. Conclusion

Estimated heat equivalent of 1% per day boil-off for 100 litre LHe stored in cryostat at working pressure of 1 bar is 0.03014 W. Hence the excess of thermal load over and above the normal boil-off load would be 0.4178 W(= 0.448 - 0.03014).Thus, any experiment with heat load less than 0.4178 W can be conducted using the present cryostat, with "in-situ" recondensation for any length of time, without any increase in pressure of cryostat from 1 bar and also without any need of refilling of LHe in the cryostat. Hence the objective of present research work was fulfilled.The cryocooler test needs to be conducted one more time by actually filling LHe in the cryostat. It is expected that as the 4.2 K boil-off Helium vapour will also be reaching the 1ststage of cryocooler, shield temperature will drop down further and may improve the cryostat performance.

8. References

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