T.1: Cryocooler Development at RRCAT

P K Kush (kush@rrcat.gov.in), R S Doohan, R C Sharma and S G Gilankar.

Several scientific and technological applications require low temperatures in the range of 10 K - 70 K, with rather modest heat load requirements of a few watts. One important example is cooling of devices like infra-red optical detectors, parametric amplifiers and cryopumps. Cryocoolers are particularly convenient and economical systems for this purpose as they dispense with the need of Liquid Helium and the problems associated in the handling of liquid Helium. Cryocooler need only electricity to produce such low temperatures. In view of the immense potential of cryocoolers, their development was taken up at RRCAT. Two types of Cryocoolers, 30K and 10K, were developed at Cryo-engineering and Cryo-module Development Section (CCDS).

One of the simplest method for producing low temperature is by cooling with Joule-Thomson (J-T) expansion, where the gas is made to expand from a high-pressure region to a low-pressure region through a constriction. This method however requires that the expanding gas be below its inversion temperature. Helium is the only gas that can produce temperatures below 20K. It has an inversion temperature of 40K. Use of J-T expansion for producing low temperature using Helium gas will, therefore, require it's pre-cooling below 40K. In addition J-T expansion process is one of the most inefficient cooling process. The gas can also be cooled by being made to do external work. In contrast to J-T expansion the later method always results in lowering of temperature and does not require any pre-cooling. This work can be done in an expansion engine or turbine as in Claude cycle. The systems based on this cycle have high refrigeration efficiency ~25% (for air liquefaction systems), but are complicated to fabricate as they operate at higher rpm, and consists of seals, valves etc. working at low temperature. Further, they are very bulky and are not suitable for cooling small systems. For cooling of small size detectors /amplifiers, a more compact system was designed and first reported by Gifford and McMahon in 1959. Although, it has very small efficiency, this system is widely used for small capacity cryocoolers. Apart from compactness it works at a lower rpm (60 - 120 rpm), which results in less wear and tear and hence allows long continuous operating period.

A schematic of such a system is shown in Fig.T.1.1. It basically consists of two major subsystems; an Expander Module and a Compressor Module. The compressor Module provides continuous supply of oil-free helium gas to the Expander module through two valves `A' (High Pressure - HP) and `B' (Low Pressure - LP). The Expander module consists of a cylinder and a hollow displacer, which is filled with stacked Cu mesh. This displacer divides the expander volume into two viz. Volume-1 and Volume-2. The displacer moves up and down inside the cylinder with the help of a motor. The load (cryotip) is placed at the top portion of the cylinder as shown in Fig. T.1.3.

When displacer is at the top and valve A is open (valve B closed), high-pressure helium gas enters through valve A and fills the Expander. At this time the displacer is made to descend by the motor, with the valve A still kept open as shown in Fig.T.1.2. The gas in volume 1 enters the volume 2 through the regenerator. Once the displacer reaches the lower end, the valve A closes and the valve B opens, thus connecting

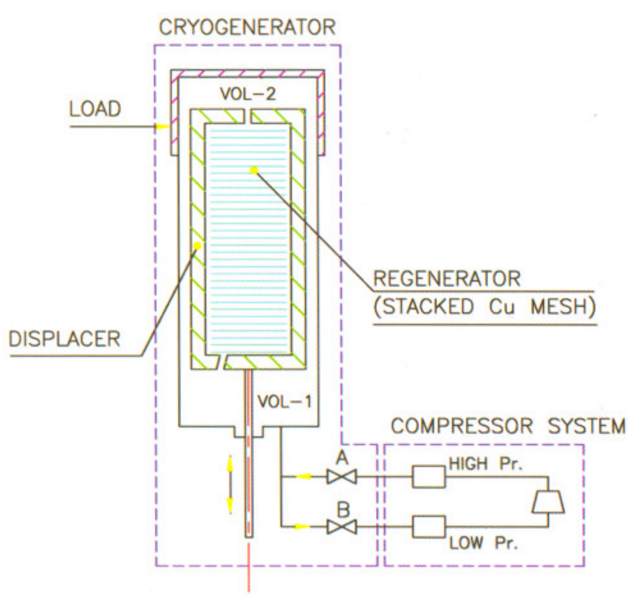

Fig. T.1.1: Schematic Diagram of G-M Cryocooler

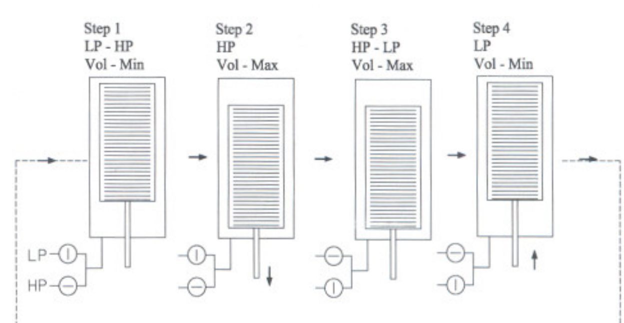

Fig. T.1.2: Sequence of Operation for Gifford McMahon Cycle the Expander module to the lower suction pressure of the compressor system. The gas within the Expander, does work to push out the gas that leaves during this process; therefore, energy is removed as work from the gas finally left in the expansion space. This causes the temperature of the lower pressure gas remaining in the expansion space (Volume 2) to drop to a lower temperature. Now the displacer starts moving upwards, forcing the gas in volume 2 to pass through regenerator. During this passage gas cools the regenerator. In the next cycle when valve A opens, and the displacer is made to descend. The high-pressure gas, passes through regenerator to fill in volume 2 and gets cooled by the regenerator, which was cooled by the outgoing cooled gas in the previous cycle. Once the displacer reaches the lower end, valve A closes and valve B opens, cooling the gas further by expansion. Now the displacer starts moving upwards, forcing the cooled gas in volume 2 to pass through regenerator thereby cooling it, and the cycle repeats. In a single expansion stroke the temperature of gas drops only by about 6 - 8 degrees. This cools the regenerator and after repeated cycles a steady state is reached. In steady state, if for example the machine is operating at 50 K, the gas cools from 300K to 50K in the regenerator itself and the temperature would further drop by 6 - 8 degrees due to expansion. Warming up of this cooled gas to the steady state temperature of 50K represents the actual refrigeration load. The regenerator should be designed to have very high efficiency (typically 99.7%).

A small loss in regenerator efficiency results in a very high loss in refrigeration. Typically a single stage Cryocooler can be used to obtain 30K with reasonable cooling capacity. A cascaded two stage system is required to obtain lower temperatures, say down to 10K with reasonable cooling capacity. Vacuum insulation is provided around the cryotip.

Cryocoolers developed at RRCAT are shown in the photographs in Fig.T.1.4. Two models of 30 K Cryocooler are developed. The first model produces a lowest temperature of 28K, its cooling capacity at different temperatures is shown in Table 1. The second version produces a lowest temperature of 25K, its cooling capacity is also shown in Table T.1. A 10K Cryocooler model has also been developed. It produces a lowest temperature of 8K. Its cooling capacity at 10K temperatures is 1.5W (Fig.T.1.5)

Table T.1: Cooling capacities of 30K Cryocoolers developed at RRCAT

Normal Mode	Optimized Mode
Model 01	
3W at 50K	3W at 30K
	8W at 50 K
Model 02	
5W at 30K	10W at 35K
17W at 50 K	20W at 50 K

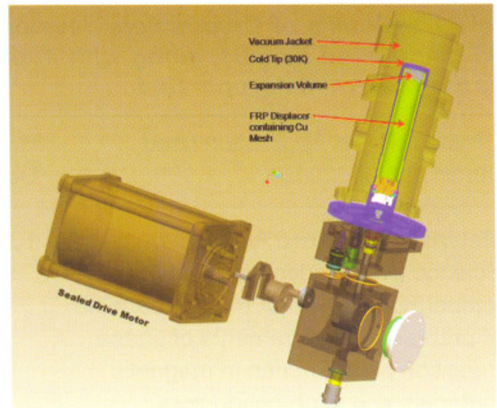

Fig. T.1.3: 3D model of Cryocooler developed at RRCAT

The 30K Cryocooler expander consists of a single stage expansion space (Fig. T.1.3). In this copper mesh is used as regenerator material. The 10K Cryocooler expander has two cascaded expansion spaces. In the first expansion space, about 50K is achieved while in the second expansion space

Fig. T.1.4: Photograph showing 30 K Cryocooler Developed at RRCAT

Table T.1.2: Details of Cryocoolers developed by CCDS being used by labs, along with number of hours they have already operated.

S. no	Division Name/ Application used (as on Jan 01, 2010)	Hours Operated
1.	Materials, Advanced Accelerator Science Div.: Working over a wide temperature range (30-400K), capable of precision measurements of phase transition phenomenon in magnetic materials and superconductors	1063 hrs
2.	Semiconductor Laser Section: Temperature Dependent Electrical Transport measurements on semiconductors thin films and optoelectronic structures like lasers, detectors - Regularly grown using MOVPE system at RRCAT	684 hrs
3.	Laser Physics Applications Division: Temperature Dependent Carrier Dynamics measurements by Ultra Fast Pump Probe Spectroscopy	613 hrs
4.	Photoluminescence setup at BARC Spectroscopy Lab RRCAT Indore: Cryocooler is coupled to a specrofluorometer of Jobin-Vyon (Model no-Fluoromax-3) suitable for experiments in Temperature range of 40 to 300K	600 hrs
5.	Laser Physics Applications Division: Temperature Dependent Transient Photoconductivity & Photoluminescence of Organic Semiconductors	540 hrs
6.	Materials, Advanced Accelerator Science Div.: Resistivity versus Temperature measurements.	400 hrs

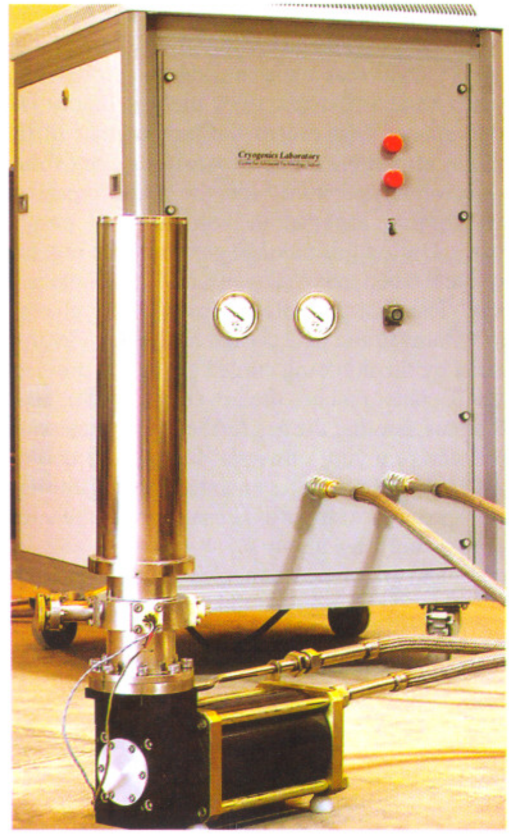

Fig. T.1.5: 10 K Cryocooler Developed at RRCAT

temperatures lower than 10K is achieved. Here also, copper mesh is used as first stage regenerator material. As copper loses its specific heat very fast below 50 K, lead balls are used as the second stage regenerator material. Lead has higher volumetric specific heat as compared to copper below 50K.

A Compressor module is required to supply pure and oil free high pressure helium gas to the expander modules for their operation. Suitable compressor modules are also developed indigenously, as helium compressor for use in such system are not available in the open market, due to their propriety nature.

Hermetically sealed air conditioner compressors available in the market for Freon gas are used in our compressor modules after suitably modifying them for helium gas compression. Helium gas has very high heat of compression as compared to Freon (Cp/Cv = 1.17 for Freon 22 and 1.67 for Helium). This results in very high exhaust gas temperature. If left unchecked this high temperature not only degrades the lubricating oil, but due to the increased vapor pressure of lubricating oil, it migrates to the expander, leading to temperature fluctuations. To overcome this problem, instead of compressing helium

Fig. T.1.6: Cryopump developed at CCDS using 10K Cryocooler.

TableT.1.3: Specifications of the Cryopump Developed using Cryocooler developed at RRCAT:

- Ultimate Vacuum: 4 x 10E-8 mbar
- Pumping Speed
  - Nitrogen: 1200 Liter/sec
  - Argon: 900 Liter/sec
- Max. Throughput: 2 mbar. Liter/sec
- Impulsive gas load (Cross over) Tolerance: 60 mbar-Liter
- Gas Capacity for Nitrogen: 300 Std. liters

gas alone, oil gas mixture is compressed. Oil having higher mass specific heat in the mixture, caries bulk of the heat produced during compression. Now this oil has to be cooled to ambient temperature and returned to the compressor for continues maintenance free operation. Before the high pressure helium gas is passed to the expander module, traces of oil have to be removed from it, typically to a level of less than 5 ppm. This has been achieved successfully by us. Selection of the lubricating oil as well its processing is a complicated task. Proper selection as well establishing the process parameters, along with processing procedures is another time consuming task. Now cryocoolers developed by us are suitable for maintenance free operation over several thousands of operating hours. All our systems, 30 K as well 10K cryocoolers, developed by us have a very good temperature stability (temperature remains stable within ± 0.5 K) when operated continuously round the clock for weeks. Six numbers of 30K cryocoolers supplied to users labs are working satisfactory since last several years (Table T.1.2).

A refrigerator operated cryopump using 10K cryocooler is also developed. Its specifications, practically achieved, are given in table 3 and the system is shown in Fig.T.1. 6.

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