

# Development of helium refrigeration/ liquefaction system at BARC, India

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**Abstract.** An experimental helium refrigerator/liquefier, using ultra high speed cryogenic turboexpanders, is designed and developed at Cryo-Technology Division, BARC. The developed system is based on the modified Claude cycle. The developed system is presently fully functional consisting of process compressor with gas management system, coldbox, helium receiver Dewar, tri-axial transfer line and helium recovery system. Extended trial runs are conducted to evaluate the performance of the developed system. During these trials, liquefaction rate of around 32 l/hr and refrigeration capacity of around 190W is achieved. The paper addresses design, development and commissioning aspects of the developed helium liquefier along with results of performance evaluation trial runs.

## 1. Introduction

A helium liquefaction system based on modified Claude cycle is developed at Bhabha Atomic Research Centre (BARC), India to cater to requirements of RF cavity and superconducting magnet cooling applications. The developed system consists of a pre-cooler turbo expander and two process turbo expanders in series with an intermediate multi-stream plate fin heat exchanger. Most of the components of the helium liquefier are developed either in-house or with local vendors. The paper addresses design, development, commissioning aspects and performance evaluation of the developed system.

## 2. Process description

The process schematic of the developed system is shown in figure 1. The system consists of a pre-cooler turboexpander and two process turboexpanders. The HP helium gas, from the exit of oil flooded helium screw compressor and fine oil removal system, enters the heat exchanger located inside the super insulated coldbox. This HP stream is cooled in the series of plate fin heat exchangers (PFHE 1-3) and then gets purified further in the activated charcoal bed (ACB-1). This pure helium stream then bifurcates into two streams. One stream goes to a series of two turboexpanders while the other stream goes to two Joule Thompson valves (JT valves) in series. These two streams are cooled in PFHE-5 by return LP cold stream coming from the LHe receiver Dewar. The stream, going to the series of



turboexpanders, expands through the first turboexpander (TEX-1) before entering PFHE-5 as MP stream. The stream, going to the first JT valve, passes through PFHE-4 before entering PFHE-5 as HP stream. The MP stream, after exiting from PFHE-5, expands further in the second turboexpander (TEX-2) before mixing with the return LP stream at the LP inlet of PFHE-6. The HP stream, after exiting from PFHE-5, further cools down in the PFHE-6 and PFHE-7 before entering first JT valve (BSCV-7). After BSCV-7, the HP stream cools down in the PFHE-8 and then expands in the second JT valve (BSCV-9). In the BSCV-9, part of the HP stream liquefies. The two phase helium is transferred through a tri-axial transferline to the LHe receiver Dewar. The LHe is collected in the LHe receiver Dewar and the low pressure helium vapor returns to the compressor suction via the heat exchangers while cooling the incoming high pressure helium streams.

A by-pass valve BSCV-6 is provided to bypass the last two heat exchangers during initial cool down when the lowest temperature is above maximum inversion temperature for helium. A bypass valve BSCV-8 is provided before second JT valve (BSCV-9) to bypass the LHe receiver Dewar during initial experiments when the coldbox is not connected with the LHe receiver Dewar. A pre-cooler turboexpander is also provided which can be used to enhance the plant capacity by using extra available pressure head.

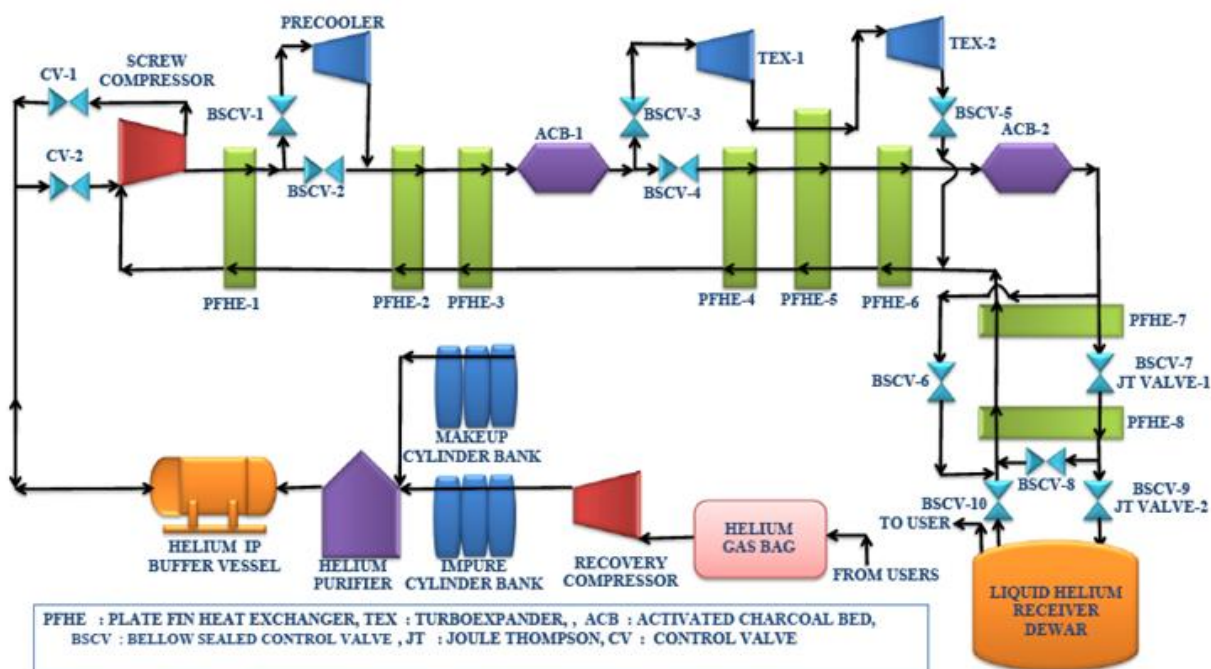


Figure 1. Process schematic of the developed helium refrigeration/ liquefaction system

Gas management system consists of three buffer vessels of 20 m<sup>3</sup> capacity each. These buffers are filled with helium gas up to 8 Kg/cm<sup>2</sup> pressures through helium quads having 56 cylinders of 10 Nm<sup>3</sup> capacity. The process compressor is connected to these buffers through two control valves for closed loop control of process compressor. The used/excess gas from users, Dewar vent and safety valves is collected in two helium gas bags of 35 m<sup>3</sup> capacity each. The gas from the gas bag is filled in impure helium quads through recovery compressor. The impure gas from impure quad is purified with liquid nitrogen cooled external helium purifier and subsequently stored in helium buffer vessels. Before starting the plant, gas is purified with LN<sub>2</sub> cooled external purifier [18]. The moisture level after purification is less than 1 ppmv (as per moisture meter) and N<sub>2</sub> impurity (as per multi component impurity detector, MCID) is 1-2 ppmv.

## 2. Major components developed at Bhabha Atomic Research Centre (BARC)

Cryo-Technology Division (CrTD), BARC has been working on development of various cryogenic components for helium refrigeration systems. Various research papers are published/ presented by CrTD, BARC related to development of these components/ systems [1-21].

### 2.1. Turboexpanders

Ultra high speed cryogenic turboexpanders are one of the most important components in a modern large scale cryogenic system. Turboexpanders based on aerodynamic gas bearings are developed at BARC. Various components of turboexpanders are manufactured in-house using precision machining facilities such as 5 axis milling machine for turboexpander 3-d profile. Photographs of various developed turboexpander wheels are shown in figure 2. Dynamic balancing of turbo expander shaft, turbine and brake wheel assembly is done using specifically developed precision balancing facilities. Balancing in the order of mg-mm is achieved in the developed balancing facilities. Rotor-dynamic performance of the turboexpanders is evaluated in closed loop test facilities before installation in the developed helium refrigerator/ liquefier. In the developed helium refrigerator/ liquefier, the pre-cooler is used to augment liquefaction/refrigeration capacities by making use of higher available process compressor pressures. For normal runs, pre-cooler is excluded from the circuit. During system performance evaluation, performance of turboexpanders is also evaluated. Vibration of turbo expanders is continuously monitored using OROS make vibration analyzer (Model number OR36). The process turbo expanders are designed for refrigeration mode operation. Comparison of turboexpander performance during refrigeration and liquefaction experimental runs with their basic design specifications is shown in table 1.



Figure 2. Photographs of the turboexpander wheels used in the developed system

Table 1. Comparison of turboexpanders performance with designed parameters.

Parameters	Design	TEX-1		Design	TEX-2	
		Max. Ref.	Max. Liq.		Max. Ref.	Max Liq.
Inlet pressure (MPa)	1.2	1.013	1.141	0.649	0.491	0.637
Exit pressure (MPa)	0.65	0.492	0.638	0.195	0.170	0.242
Inlet temperature (K)	44.6	46.0	59.9	12.8	9.18	14.9
Exit temperature (K)	37.8	37.8	51.9	9.0	6.71	11.46
Rotational speed (rpm)	260000	266820	251040	168000	139800	156060
Turbine major diameter (mm)	16	---	---	16.5	---	---
Flow rate (g/s)	45	46.74	46.42	45	46.74	46.42
Power developed (W)	1620	2044	2005	720	376	719
Isentropic efficiency	70%	71.6%	65.6%	70%	60.8%	65.9%

## 2.2. Coldbox

The coldbox for the developed system is designed, produced and tested in-house. The coldbox which houses the cryogenic process piping and equipment is designed for maintaining high insulating vacuum condition. The vacuum vessel (1.5 m in diameter and 2.3 m in length) is fabricated and tested as per ASME Section VIII, Div-I [20]. It is properly cleaned, buffed and baked to reduce the out gassing. The process piping and equipment are supported from top through 40 mm thick top cover of coldbox vessel. The pipes and valves which come out of the coldbox are connected to top cover through thin sleeves to reduce distortion during welding and to reduce axial conduction heat losses. The computer generated 3-d model, fabricated piping assembly and MLI wrapped assembly are shown in figure 3. Based on piping and instrumentation diagram, coldbox dimensions as well as piping layout is optimized for compactness, ease of operation and maintenance, ease of fabrication, multilayer super insulation wrapping and heat in-leak mitigation, etc. The piping design and fabrication is done as per process piping code B31.3 [21]. The flexibility and stress analysis of the process piping is done using piping systems stress analysis software. The material for process piping is SS304L. The fabrication is done using TIG welding technique with pure argon gas purging and shielding. Individual subassemblies are fabricated and leak tested up to  $10^{-9}$  mbar.liters/sec in vacuum mode and up to  $10^{-6}$  mbar.liters/sec in sniffer mode. The subassemblies are set up in the top cover and welded together to form the final piping assembly. The piping assembly is then subjected to pressure hold and pneumatic testing as per B31.3 [21]. The piping is tested for leak tightness using pressure hold, vacuum hold and mass spectrometer leak detection (MSLD). All the heat exchangers are supported by top cover through spring type supports to allow for thermal contraction during cool down. The flow rates through the turboexpanders and JT valves are measured by orifice plates installed in the piping. The tapping for pressure transmitters and differential pressure transmitters is taken at various places through 6 mm tubing. For temperature measurement copper blocks conforming to the outside diameter of pipes are silver brazed to the pipes and sensor elements (Silicon diode) are screwed to these blocks. The sensor leads are then taken out of the coldbox top cover through multi-pin electrical feed-throughs. Heat in-leaks are controlled by using multi-layer super insulation. Vacuum of the order of  $10^{-6}$  mbar is maintained in the coldbox using turbo molecular pump backed with rotary vane pump (TMP system: ALCATEL make TURBOSTAND ATP-900). 20 layers of both side coated aluminised mylar with polyester net spacer are wrapped to the inside diameter of the coldbox vessel. The piping assembly is also wrapped with multilayer super insulation. The higher temperature heat exchangers and other piping components are wrapped with 20-30 layers while the lower temperature heat exchangers, pipings are wrapped with 10 layers. The developed system is as shown in figure 4.

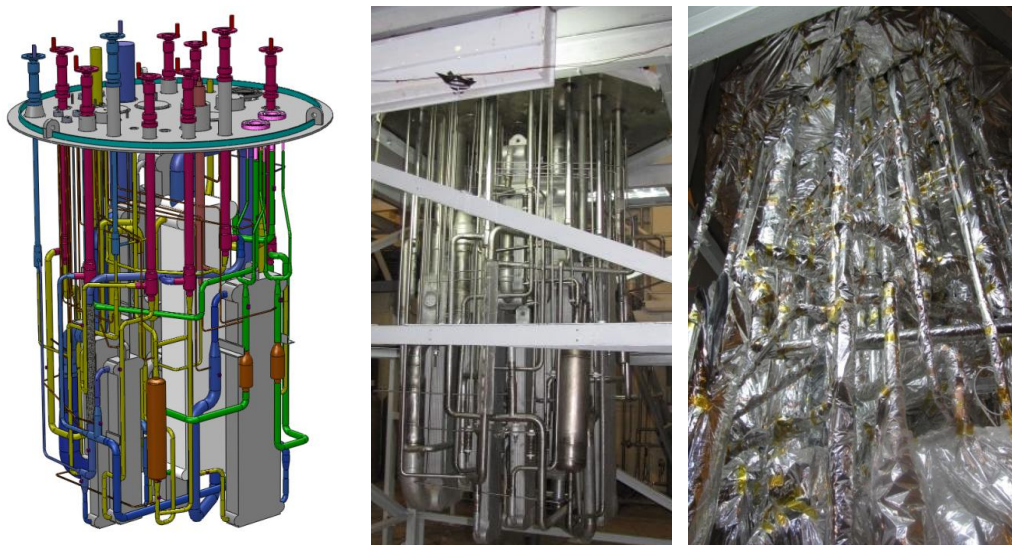


Figure 3. Photographs of the developed coldbox piping





Figure 4. Developed helium refrigeration/liquefaction system

### 2.3. Multistream plate fin heat exchanger

Multistream plate fin heat exchanger (PFHE-5) is designed in-house and fabricated locally by M/s Apollo heat exchangers, Vasai. Photograph of the developed PFHE is shown in figure 5. Construction details of the used multistream PFHE-5 are described in Table 2. Performance of this heat exchanger is evaluated during performance evaluation of the developed system. There is a good match between experimentally measured and numerically predicted performance of multistream PFHE. Measured exit temperatures of different streams match within measurement accuracy of temperature sensors with the predicted exit temperatures.

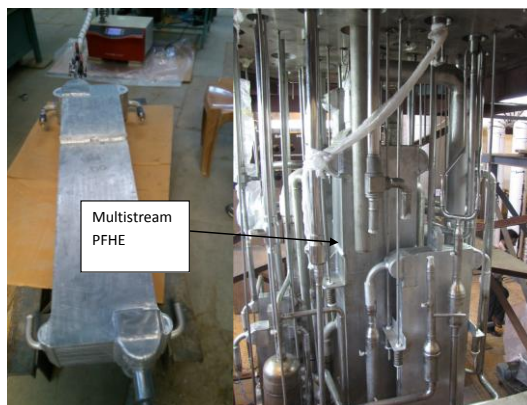


Figure 5. The developed multistream PFHE (Left) undergoing leak detection; the PFHE mounted on the coldbox top cover (Right) along with other piping.

Table 2. Construction details of the multistream PFHE.

[illegible]

#### 2.4. Tri-axial transfer line

A transfer line for transfer of helium between coldbox and LHe receiver Dewar is developed in-house [19]. The cryogenic coupling (female) is welded on the coldbox flange and facilitates disassembly of the transfer line from coldbox vessel. One end of the transfer line is welded to the cryogenic coupling (male) and the other end enters the Dewar vessel through a Goddard coupling. The alignment of the cryogenic coupling to the coldbox flange affects the assembly of the coldbox with the transfer line and Dewar and shall be taken care of during fabrication. The transfer line has three coaxial pipes, innermost one transfers two phase helium to Dewar, the vapour flows from the Dewar to coldbox through the second coaxial pipe and the third pipe is for vacuum insulation (vacuum with MLI and activated charcoal fabric wrapped on middle tube). G10 spacers (1 mm thick) are provided in the vacuum region. No spacers are required between the middle line and the innermost line since they are at the same operational temperature. The welding and subsequent MSLD of the transfer line is carried out in stages. All welds are manual TIG welds and leak tested before they become inaccessible in the next step of assembly. The weld joints are helium leak tested up to  $10^{-8}$  mbar l/sec. Utmost care is taken during welding of outer tube by providing metallic barrier to protect MLI. The fabricated transfer line is as shown in figure 6.

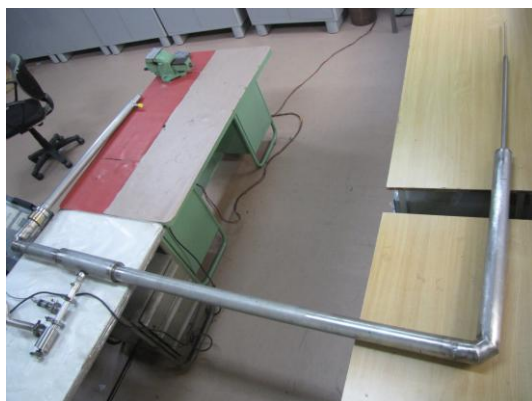


Figure 6. Photograph of developed tri-axial transferline

#### 2.5 Other components/ facilities utilized in the development of helium liquefier

During development of helium liquefier various facilities/ components at CrTD, BARC are utilised. These include, closed loop test facilities for evaluation of rotor-dynamic and thermal performance of the turboexpanders before installation in the developed helium refrigerator/ liquefiers, closed loop low temperature heat Exchanger test facility for evaluation of thermal performance of developed plate and fin heat exchangers, precision rotor balancing facility (Hard bearing, soft bearing and in-situ machines), rotor speed measurement and vibration analyzers, precision machining facility, metrology facility (roundness tester, precision measuring instruments, measoroscope, height master, etc), vacuum systems and mass spectrometer leak detection facility (vacuum and sniffer mode) for leak detection of various cryogenic components and process piping, clean tent for coldbox fabrication and super insulation wrapping, multi component impurity detectors, dew point meters and oxygen monitors, other standard utilities like instrumentation air, cooling water and chilled water.

### 3. Performance evaluation of developed helium refrigeration/ liquefaction system

After series of trials, liquefaction of helium gas was achieved on 21<sup>st</sup> of September, 2015 midnight after about 15 hrs of operation. Collection of liquid helium in Dewar was started on 26<sup>th</sup> September, 2015 at around 14:00 hrs. The measured liquefaction rate was around 20 l/hr. The total process compressor flow was about 38 g/s. Turbine isentropic efficiencies were 67% and 60% respectively. About 600 liters of LHe was collected and subsequently level was maintained through heater for a week. During this run, due to non-availability of chilled water, turboexpanders were operated at reduced speeds to avoid over heating of turboexpander housing. LHe level in the 1000L LHe receiver Dewar is measured with the superconducting level sensor and transmitter. Helium liquefaction rate is

estimated by measuring the LHe level in the LHe receiver Dewar. Helium liquefaction rate is also verified by measuring the drop in the pressure of the buffer vessel supplying the make-up gas during helium liquefaction. In the refrigeration mode, refrigeration load is applied through a Kapton® (Polyimide film) insulated flexible heater dipped in the LHe of the LHe receiver Dewar.

In the second trial run in the last week of October, 2015, chilled water was made available and turbines could be operated at design speeds. Pre-cooler turbine was used only during cooling down. It was possible to validate the helium liquefaction process for its most standard mode of operation, i.e., with two turbines. Measured helium liquefaction rate of about 32.7 l/hr and refrigeration capacity of about 193 W@ 4.8K was achieved during this trial. Maximum isentropic efficiency of 72% was achieved for TEX-1 at speeds exceeding 4600 Hz. Both the turboexpanders exhibited efficiency in excess of 67% even during off-design conditions. Snap shot of turboexpander vibration signature and speed along with LHe level indicator is shown in figure 7.

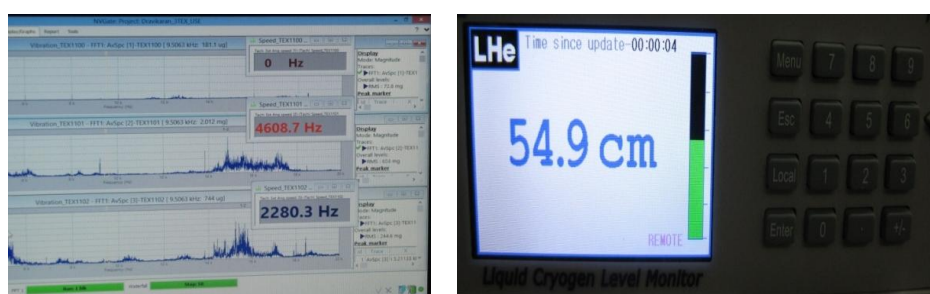


Figure 7. Turboexpander vibration signature and speed (L) Liquid level (R)

To test the long term reliability of the system, the plant was operated round the clock from 29<sup>th</sup> Jan, 2016 to 02<sup>nd</sup> march, 2016. During this run, the measured liquefaction rate was around 32 l/hr. Around 400L of LHe was collected and subsequently the level in the LHe receiver Dewar was maintained using process heater. In the refrigeration mode, the refrigeration capacity was around 160-180 watts. During this run, the vacuum system was isolated and good vacuum hold without active pumping was achieved. This is due to cryo-pumping in the charcoal, which is wrapped on the cold helium return piping.

#### 4. Conclusion

A helium liquefier/refrigerator based on high speed turboexpanders and compact plate fin two stream and multistream heat exchangers was developed by BARC, India. During operational trials, it was possible to achieve around 32 l/hr of liquefaction and about 190 W of refrigeration at 4.8 K without any pre-cooling. The turboexpanders and heat exchangers in the process performed reasonably well during the trials. Further studies on operational data are under way to analyze in details different aspects of plant performance such as heat in-leak at different sections of the plant, pressure drop mapping, efficiency of all equipment, etc. Work is also underway to convert the presently manually operated plant to a completely automated one. As we gain operational experience and with ongoing improvement efforts, we expect that the plant efficiency will improve.

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