Development of Helium Refrigeration and Liquefaction System at BARC

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An experimental helium refrigerator and liquefier, using ultra high speed cryogenic turboexpanders is designed and developed in BARC. The system is based on the Modified Claude Cycle 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 system. During these trials, liquefaction rate of around 32 l/hr and refrigeration capacity of around 190W@4.8K is achieved. The long term reliability of system is ensured by running the plant round the clock for a month. The article addresses design, development and commissioning aspects of the liquefier along with results of performance evaluation trial runs.

Introduction

Turboexpander based helium liquefaction system is developed in BARC to cater to cooling requirements of radio frequency (RF) cavity and superconducting magnet being developed at BARC. This system is based on Modified Claude cycle with a pre-cooler turboexpander and two process turboexpanders in series with intermediate multi-stream plate fin heat exchangers. The system consists of helium compressor with gas management system, coldbox, transfer line, helium receiver Dewar and helium recovery system. Turboexpander based helium liquefaction system is developed and demonstrated first time in India. Most of the components of the helium liquefier such as high speed turboexpanders, multi stream heat exchanger, coldbox, long stem cryogenic bellow sealed valves, helium transfer line, etc., are developed either in-house or with local vendors. During the trial runs, liquefaction rate of around 32 l/hr and refrigeration capacity of at 190W@4.8K is achieved. The design, development, commissioning and performance evaluation of the system are discussed in the following sections.

Process description

The process schematic of the system is shown in fig 1. The HP helium gas, from the exit of oil flooded helium screw compressor and fine oil removal system, enters the coldbox. This HP (High Pressure) 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). The pure helium stream then bifurcates into two - One goes to a series of two process turboexpanders while the other goes to series of heat exchangers and two Joule Thompson valves (JT valves). The two streams are cooled in multi stream heat exchanger PFHE-5 by return LP (Low Pressure) cold stream coming from the liquid Helium receiver Dewar.

The stream, going to the series of turboexpanders, expands though the first turboexpander (TEX-1) before entering PFHE-5 as IP (Intermediate Pressure) stream. The IP stream 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 stream, going to JT circuit, passes through a series of heat exchangers (PFHE 4-6).
followed by activated charcoal bed ACB-2. The stream further cools down in the PFHE-7 before entering the first JT valve (BSCV-7). Subsequently, 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 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 to enhance the plant capacity using extra available pressure head.

Gas management system consists of three buffer vessels of 20 m$^3$ capacity. They are filled with helium gas upto 8 Kg/cm$^2$ pressures through helium quads having 56 cylinders of 10 Nm$^3$ capacities.

The process compressor is connected to these buffers through two control valves for closed loop control of process compressor. The used or excess gas from users, Dewar vent and safety valves is collected in two helium gas bags of 28 m$^3$ capacity. The gas from the bags is filled in impure helium quads through recovery compressor. The impure gas from impure quads 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$_2$ cooled external purifier [17]. The moisture level after purification is less than 1 ppmv and N$_2$ impurity (as per multi component impurity detector, MCID) is 1-2 ppmv.

**Major components developed in BARC**

Cryo-Technology Division (CrTD), BARC has been working on development of various cryogenic components for helium refrigeration systems. Various research papers are published by CrTD, BARC related to development of these components and systems [1-24].

**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 in 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 turboexpander wheels are shown in fig. 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 balancing facilities. Rotor-dynamic performance of the turboexpanders is evaluated in closed loop test facilities before installation in the helium refrigerator/liquefier. In the 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.

![Fig. 2. Photographs of the turboexpander wheels used in the developed system](image-url)
During system performance evaluation, vibration of turboexpanders is continuously monitored using OROS make vibration analyzer (Model Number: OR36). The process turboexpanders are designed for refrigeration mode operation. Comparison of turboexpander performance during experimental refrigeration and liquefaction runs with their basic design specifications is shown in Table 1.

### Coldbox

The coldbox, which houses the cryogenic process piping and equipment for maintaining high insulating vacuum condition, is designed, developed and tested in-house. 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 [25] standard. 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. 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 Fig. 3.

Based on piping and instrumentation diagram, coldbox dimensions and piping layout are 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 as per process piping Code B31.3 [26]. 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 with pure argon gas purging and shielding. Individual subassemblies are fabricated and leak tested up to 10⁻⁶ mbar.liters/sec in vacuum mode and up to 10⁻⁸ mbar.liters/sec in sniffer mode. The subassemblies are set up in the top cover and welded together to form the final piping assembly, which is then subjected to

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TEX-1</th>
<th>TEX-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit pressure (MPa)</td>
<td>1.2</td>
<td>1.013</td>
</tr>
<tr>
<td>Inlet temperature (K)</td>
<td>0.65</td>
<td>0.492</td>
</tr>
<tr>
<td>Exit temperature (K)</td>
<td>44.6</td>
<td>46.0</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
<td>37.8</td>
<td>37.8</td>
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<tr>
<td>Turbine major diameter (mm)</td>
<td>2600000</td>
<td>266820</td>
</tr>
<tr>
<td>Flow rate (g/s)</td>
<td>16</td>
<td>---</td>
</tr>
<tr>
<td>Power developed (W)</td>
<td>1620</td>
<td>2044</td>
</tr>
<tr>
<td>Isentropic efficiency</td>
<td>70%</td>
<td>71.6%</td>
</tr>
</tbody>
</table>

Table 1. Comparison of turboexpanders performance with designed parameters.
pressure hold and pneumatic testing as per B31.3 \[26\]. and tested for leak tightness using 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 double-sided aluminised Mylar with polyester net spacer are wrapped to the inside diameter of the coldbox. 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.

**Multistream plate fin heat exchanger**

Multistream plate fin heat exchanger (PFHE-5) shown in fig. 4 is designed in-house and fabricated by M/s Apollo heat exchangers, Vasai. Construction details of the multistream PFHE-5 are described in Table 2. Performance of this heat exchanger is evaluated during performance evaluation of the 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.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Heat Exchanger Matrix Metal</td>
<td>Aluminium (3003)</td>
<td>Fin Height</td>
<td>3.6 mm</td>
</tr>
<tr>
<td>Core Length</td>
<td>1335 mm</td>
<td>Serration Length</td>
<td>3 mm</td>
</tr>
<tr>
<td>Core Width</td>
<td>300 mm</td>
<td>Fin Pitch</td>
<td>1.4 mm (As)</td>
</tr>
<tr>
<td>Side Bar Width</td>
<td>10 mm</td>
<td>Total No. of Layers</td>
<td>39</td>
</tr>
<tr>
<td>Total Width</td>
<td>320 mm</td>
<td>No. of Layers for LP</td>
<td>20</td>
</tr>
<tr>
<td>Separating Plate Thickness</td>
<td>0.8 mm</td>
<td>No. of Layers for HP</td>
<td>13</td>
</tr>
<tr>
<td>End Plate Thickness</td>
<td>5.8 mm</td>
<td>No. of Layers for HP</td>
<td>6</td>
</tr>
<tr>
<td>Fin Type</td>
<td>Serrated</td>
<td>Fin Metal Thickness</td>
<td>0.2 mm</td>
</tr>
</tbody>
</table>

Table 2: Construction details of the multistream PFHE.

**Fig. 4:** The developed multistream PFHE (Left) undergoing leak detection; the PFHE mounted on the coldbox top cover (Right) along with other piping.
**Tri-axial transfer line**

A helium transfer line shown in fig. 5 is developed in-house [22]. The cryogenic coupling (female) is welded on the coldbox flange to facilitate disassembly of the transfer line from coldbox. One end of the transfer line is welded to the cryogenic coupling (male) and the other end enters the Dewar through a Goddard coupling. 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 are assembled. 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.
Performance evaluation of helium refrigeration/liquefaction system

After a series of trials, liquefaction of helium was achieved on 21st of September 2015 after about 15 hrs of operation and liquid helium first collected on 26th September, 2015. 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. LHe level was measured using a superconducting level sensor and transmitter. In the refrigeration mode, refrigeration load is applied through a Kapton® (Polyimide film) insulated flexible heater dipped in the LHe.

In the second trial run during 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 fig. 7. To test the long term reliability of the system, the plant was operated round the clock from 29th Jan, 2016 to 02nd 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 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 by cryo-pumping in the charcoal, which is wrapped on the cold helium return piping.

Subsequently, three more trial runs are successfully conducted. Around 200 L of LHe is used for performance evaluation of the LHe Dewar. During the latest operation in the month of March 2017, 500L LHe helium is transferred online to two 250L LHe Dewars for conducting the experimental performance of superconducting magnets developed by Accelerator Control Division, BARC.

Conclusion

A helium liquefier and refrigerator, based on high speed turboexpanders and compact plate fin two stream and multistream heat exchangers, is developed by CrTD, BARC. During operational trials, liquefaction capacity of around 32 l/hr and refrigeration capacity of about 190 W@ 4.8 K without any pre-cooling is achieved. The turboexpanders and heat exchangers in the process performed reasonably well during the trials. Work is 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 further improve.

References


25. The American society of mechanical engineers Rules for construction of pressure vessels 2003 ASME Sec VIII Div