Helium refrigeration system for hydrogen liquefaction applications

J Kumar, SR Nair, RS Menon, M Goyal, NA Ansari, A Chakravarty and V Joemon
Cryo Technology Division, Bhabha Atomic Research Centre, Mumbai, India
jitenk@barc.gov.in

Abstract. Liquid hydrogen around 20 K is used as cold moderator for generating “cold neutron beam” in nuclear research reactors. A cryogenic helium refrigeration system is the core upon which such hydrogen liquefaction applications are built. A thermodynamic process based on reversed Brayton cycle with two stage expansion using high speed cryogenic turboexpanders (TEX) along with a pair of compact high effectiveness process heat exchangers (HX), is well suited for such applications. An existing helium refrigeration system, which had earlier demonstrated a refrigeration capacity of 470 W at around 20 K, is modified based on past operational experiences and newer application requirements. Modifications include addition of a new heat exchanger to simulate cryogenic process load and two other heat exchangers for controlling the temperatures of helium streams leading out to the application system. To incorporate these changes, cryogenic piping inside the cold box is suitably modified. This paper presents process simulation, sizing of new heat exchangers as well as fabrication aspects of the modified cryogenic process piping.

1. Introduction
The cryogenic helium refrigeration system catering to the process heat load at around 20 K is of vital importance for the cold neutron (less than 5 meV) scattering facility. The facility is very efficacious in the microscopic investigation of materials at atomic length scale and low energy neutron dynamics in a given sample [1]. In cold moderator applications, for cold neutron sources, cold helium gas from a helium refrigerator is sent to a heat exchanger where gaseous hydrogen (or deuterium) is condensed into liquid. This pool of liquid hydrogen is used as a moderator around the neutron beam in the reflector region of the research reactor [2], and produces a low energy neutron beam. Such helium refrigerators are also used for decontamination of used moderator in the nuclear power reactors. In these applications, cold helium gas from the helium refrigerator is sent inside a distillation column, where cryogenic distillation is used to remove the radioactive impurities and thus enhancing operational safety.

An existing helium refrigerator is being modified at BARC for such applications. Developmental works related to these modifications are reported in the present paper.

2. Description of the existing system
A helium refrigerator based on reverse Brayton cycle was developed at BARC, Mumbai [3, 4]. The process cycle consists of two stage expansion using high speed cryogenic turboexpanders and two
vacuum brazed aluminium plate fin heat exchangers (PFHE). The high pressure (HP) helium gas is cooled in the first PFHE by the returning low pressure cold stream before expanding in the first TEX. The HP helium gas is further cooled in the second PFHE before expanding through the second TEX. The cold helium gas, after the exit of second TEX, flows to the process load before returning to the cold box. An oil flooded helium screw compressor is used for the closed loop operation of the helium refrigerator. A fine oil removal system based on coalescers and room temperature charcoal adsorber is used to prevent the high pressure helium from carrying oil into the refrigerator coldbox. The process piping and all the cold equipment of the helium refrigerator are housed in a super-insulated vacuum vessel (coldbox). A low temperature charcoal adsorber is also used to remove the air impurities like nitrogen and traces of moisture from the process helium gas.

The capacity of the refrigeration plant was demonstrated by its continuous round the clock operation. A refrigeration capacity of 470 W at around 20 K was achieved. The process cold box along with the external piping is shown in Figure 1.

![Figure 1. Developed refrigerator coldbox with a snap shot of temperature indicator (inset) showing the lowest temperatures during an operational run](image)

3. Modifications in the existing system
The operational experiences and the need for similar cryogenic refrigeration systems for newer applications required the modifications in the earlier developed helium refrigerator. The modified
process schematic is shown in Figure 2. The modifications include the addition of PFHE-3 (simulation HX) for process load simulation. The PFHE-3 simulates the re-boiler and condenser of the cryogenic distillation column for moderator decontamination applications. The HP gas is cooled in the re-boiler due to the boiling of moderator. For fine temperature control at re-boiler and condenser, two shell and coil type heat exchangers (CHE-1, CHE-2) are also incorporated. Room temperature helium is used as high temperature stream in these heat exchangers. CHE-2 can also be used to simulate the refrigeration load.

![Figure 2. Simplified process diagram of the reverse Brayton cycle based helium refrigerator at BARC](image)

4. Estimated process parameters
During the operational runs of the developed helium refrigerator, thermodynamic performance of different equipment were accessed based on the measured process parameters. The used PFHE-1 and PFHE-2 showed an effectiveness greater than 0.95 while the efficiencies of the TEX-1 and TEX-2 were found to be in excess of 0.6 and 0.5 respectively. Process computations are carried out for the modified helium refrigerator using in-house developed simulation code, based on solution of mass and energy balance equations coupled with efficiency definitions for all process equipment such as heat exchangers and turboexpanders. For the present work, heat in-leak into the system is neglected. Process calculations have been done expecting the similar thermodynamic performances of the components under slightly varying process conditions. Input performance parameters of the equipment during in the process simulation are shown in Table 1. Commuted process points are represented as a pair of pressure and temperature points on a log linear temperature vs entropy (T-S) diagram (Figure 3, 5).

| Component | Performance parameter | Value |
|-----------|-----------------------|-------|
| PFHE-1    | effectiveness         | 0.95  |
| TEX-1     | efficiency            | 0.60  |
| PFHE-2    | effectiveness         | 0.95  |
| TEX-2     | efficiency            | 0.50  |
4.1. The refrigerator is not aided by any external source of cold
The process simulation is carried out for the modified helium refrigerator. For the simulation, the mass flow rate is taken as 45 g/s. The process compressor is operating between 1.2 bar (a) suction pressure to 11 bar (a) discharge pressure. A refrigeration capacity of 500 W is computed for the refrigerant supply temperature of 18 K. The computed T-S diagram is shown in Figure 3. The refrigeration capacity decreases as the supply temperature of the refrigerator decreases. Figure 4 represents the computed variation of the refrigeration capacity with supply temperature in the range of 14 K to 20 K with the assumptions of the fixed pressure and temperature of helium at coldbox inlet and constant component performance parameter. Demonstrated capacity of the earlier plant is 470 W at around 20 K supply temperature.

Figure 3. T-S diagram and process points of the refrigerator without external source of cold.

Figure 4. Theoretical refrigeration capacity vs minimum supply temperature of the plant without the aid of external source of cold and with the assumptions of the fixed pressure and temperature of helium at coldbox inlet and constant component performance parameter.
4.2. The refrigerator aided by external source of cold

The process simulation is carried out with 500 W of external available cold (re-boiler of process column). The other process inputs are similar to the above mentioned case in which cold from external source is not available. In the re-boiler, the heat is removed from the process gas just before it expands through the TEX. For the simulation, thermodynamic performances of the components are assumed to be the same. In this condition, the computed refrigeration capacity of the refrigerator is 1020 W. The increase in refrigeration capacity is accompanied by a higher value of mean refrigeration temperature and higher temperature at TEX-1 compared to that in the subsection 4.1.

![Figure 5. T-S diagram and process points of the refrigerator with 500W of pre-cooling from external source.](image)

5. Heat exchanger for simulating the refrigeration (with pre-cooling aid) capacity of the process:

It should be possible to run the refrigerator in standalone mode without being connected to the actual process load and yet validate the maximum refrigeration capacity. It is therefore required to have arrangements integral to the refrigerator which can simulate both the refrigeration load as well as the pre-cooling capacity to be obtained from the external process application. If both the streams going out of the coldbox can be put through a counter flow heat exchanger, then the reducing temperature of the HP flow will simulate the pre-cooling, similarly the increasing temperature of LP flow across this HX, aided by an upstream heater will simulate the refrigeration load and can be conveniently used for capacity demonstration runs. The process parameters for one such heat exchanger are described in Table 2. Sizing calculation for brazed aluminum PFHE based on the above process parameters are carried out.
Table 2. Process parameters of the simulator HX.

| Process Point         | Pressure (bar) | Temperature (K) | Fluid   | Mass flow rate (g/s) |
|-----------------------|----------------|-----------------|---------|----------------------|
| Hot stream inlet      | 4.8            | 24.3            | Helium  | 45                   |
| Hot stream outlet     | 4.7            | 22.23           | Helium  | 45                   |
| Cold stream inlet     | 1.5            | 20.18           | Helium  | 45                   |
| Cold stream outlet    | 1.4            | 22.27           | Helium  | 45                   |

For the above listed parameters, a heat exchanger with effectiveness of 0.51 and a rating of 500 W would suffice for the simulation. A heat exchanger of 40% higher rating (approx. 700 W heat transfer) has been chosen to be incorporated in the coldbox. The physical parameters of the chosen heat exchanger are provided in Table 3.

Table 3. Physical parameters of the simulator HX.

| Parameter                  | Hot Stream     | Cold Stream    |
|----------------------------|----------------|----------------|
| Effective Length           | 525 mm         | 525 mm         |
| Effective width            | 69 mm          | 69 mm          |
| Fin type                   | Offset strip   | Offset strip   |
| Fin height                 | 6.5 mm         | 6.5 mm         |
| Fin thickness              | 0.2 mm         | 0.2 mm         |
| Fin density                | 614 /m         | 614/m          |
| No of layers               | 5              | 6              |
| Separating plate thickness | 0.8 mm         | 0.8 mm         |
| Side bar width             | 8 mm           | 8 mm           |
| Cap sheet thickness        | 6 mm           | 6 mm           |
| Fin material               | Aluminium 3003 | Aluminium 3003 |

6. Fabrication of coldbox piping and other components

Coldbox piping under modification is shown in Figure 6. All the piping and other components inside the coldbox are vertically suspended from the top cover of the vacuum vessel.

Figure 6. HXs, Piping and other components inside the coldbox.
The vacuum vessel is designed, manufactured and tested as per ASME Section VIII, Div. I [5]. Process piping design code ASME B31.3 [6] has been used to design and fabricate the piping inside the coldbox. The piping layout is optimized for flexibility to mitigate the thermal stress, fabrication ease, and compactness. Tungsten Inert Gas (TIG) welding technique has been used for the whole fabrication. In the welding process, argon is used for shielding and purging purposes. Radiography testing of the welds has been done to confirm the soundness of its quality. All the heat exchangers except the simulator are supported from top cover by spring and tie rods. 6 mm outside diameter tubes have been taken out of the coldbox from different locations of the process piping to measure the line pressure. To increase the effect of cryo-pumping, charcoal has been wrapped on the lowest temperature pipe inside the cold box. Pneumatic test of the process piping and helium mass spectroscopy leak detection (MSLD) test of all its welded joints are carried out.

7. Conclusion

A helium refrigerator developed by BARC, Mumbai has demonstrated a refrigeration capacity of 470 W at around 20 K. This capacity is achieved without the aid of any external pre-cooling. The refrigerator plant has now been modified to include a simulation HX (PFHE-3) and two control heaters (CHE-1 and 2) inside the cold box. Other than the ease of operation, this will also enable the plant to demonstrate its capacity in various possible modes of operation without actually connecting it to the external process load. The helium refrigerator, expected to be ready by the middle of 2016 for capacity demonstration, is being developed as a versatile machine, capable of catering to the needs of different types of applications.

8. References

[1] Lopez RA and Gibertb EP Neutron scattering: a natural tool for food science and technology research Trends in food Sci. and Technol 2009 Vol 20 (11) pp 576–86.
[2] Axmann A, Böning K and Rottmann M FRM-II: The new German researchreactor Nuclear Engineering and Design 1997 Vol 178 (1) pp 127–33.
[3] Singh T, ChakravartyA, Rajendran S, Goyal M, AnsariNA and Prasad P 2005 Development of helium liquefaction/refrigeration system at BARC Indian journal of cryogenics Special Issue Vol 1 pp 53-58.
[4] Chakravarty A and Singh T 2011 High speed miniature cryogenic turboexpander impellers at BARC Indian journal of cryogenics Vol 36 No 1-4 pp 1-9.
[5] The American society of mechanical engineers Rules for construction of pressure vessels 2003 ASME Sec VIII Div I.
[6] The American society of mechanical engineersASME code for process piping B31 Process piping 2006 ASME B31.3.