T.1: India's First Indigenously Developed Helium Liquefier

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Cryo-engineering and Cryo-module Development Section (CCDS) of RRCAT is engaged in cryogenic engineering activities of various R & D programmes in RRCAT, including Indus synchrotrons (e.g. cryogenic support required for low temperature experiments on Indus beam lines, superconducting insertion devices etc.) Local availability of technical knowhow will substantially mitigate the hindrances in research work which are often faced due to embargo problems related with cryogenic systems. To achieve this, during last few years many developments have taken place.

On August 14, 2010 Helium liquefaction was achieved, at CCDS using a completely indigenous system for the first time in the country. This system is based on reciprocating type expansion engine and uses cross counter flow type heat exchangers, based on high finned density copper tubes. The cyclic compressor is a four stage air cooled reciprocating type compressor. Its oil removal system is also designed and developed indigenously. Helium gas from commercial cylinders, as well as that recovered from user experiments, is used for liquefying, after passing it through a liquid nitrogen based gas purifier, made locally. More than 150 liters of liquid helium was collected during its maiden trial itself, while operating for more than 25 hours continuously. Details of the liquefier system and the performance of different components are presented in this article.

Liquefaction of Helium

Perhaps the easiest method to liquefy helium is to use a cascaded system in which helium gas is pre-cooled first using liquid nitrogen and then by liquid hydrogen and finally expanded through a Joule Thomson (J-T) valve, such as in case of Linde-Hampson systems. Several such pre-cooled systems were developed by Mann et al. [1]. One of the milestones in cryogenic engineering was the design and development of a helium liquefier by Samuel C. Collins, in which both the pre-cooling stages were replaced by two expansion engines.

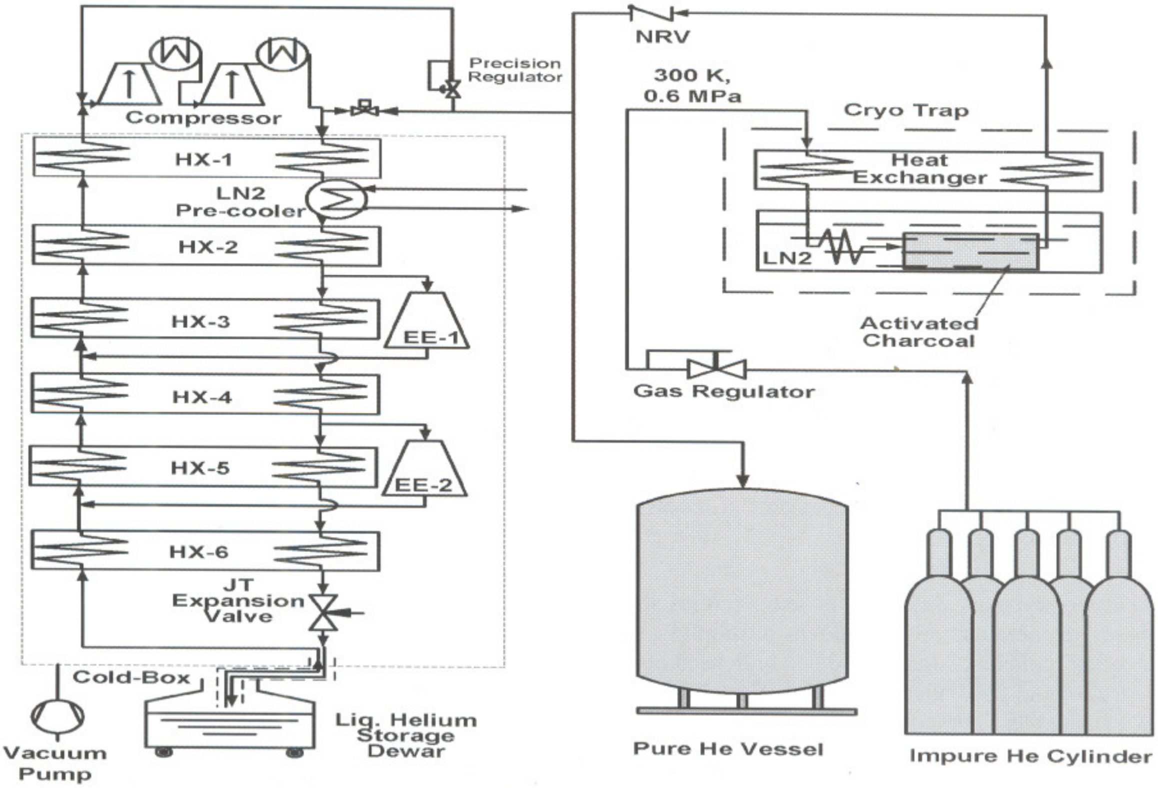

Fig.T.1.1: Schematic of a Helium Liquefier

Even today helium liquefaction systems are based straight on Collins cycle or its variants. System developed at RRCAT is also based on Collins cycle. The Collins cycle basically consists of two numbers of refrigeration producing devices called expanders, train of heat exchangers, covering a temperature range from 300K to 6K and a Joule Thomson valve. Helium gas is compressed in a cyclic compressor, also called main process compressor. Schematic of such a system is shown in Fig. T.1.1. Helium liquefaction process in this system is explained as follows. High pressure gas passes through 1st heat exchanger HX-1, see Fig. T.1.1. During the passage, it exchanges heat with outgoing low pressure gas. On exit its temperature reduces to about 80 K. At this stage it may be pre-cooled using liquid nitrogen. In a system optimised for Liquid nitrogen (LN2) pre-cooling, the liquid helium production rate can be doubled as compared to without LN2 pre-cooling, while consuming same electrical power. Then this high pressure gas passes through 2nd heat exchanger HX-2. Again it exchanges heat with cold low pressure gas return stream and its temperature reduces to about 50 K.

Now a part, about 40%, of the total gas flow passes through first expansion engine EE-1. On expansion the temperature of gas reduces to about 40K. This gas after expansion enters the low pressure gas stream, and returns to compressor suction. While passing through 3rd heat exchanger HX-3, it cools the remaining 60% high pressure gas. After cooling through 4th heat exchanger HX-4 flow is again split. About 40% of the total flow passes through the second expansion engine EE-2. Here the temperature of gas reduces to about 12K after expansion. This 12K gas cools now remaining 20% gas while passing through 5th heat exchanger HX-5. Now high pressure gas is passed through the last heat exchanger HX-6, also called J-T heat exchanger. This heat exchanger plays the most crucial part in achieving the liquefaction rate of the system. Finally, the high pressure gas expands through Joule Thomson (J-T) valve. On expansion through J-T valve, a fraction of the flow forms helium mist. This fraction depends on the temperature and pressure of helium gas at the inlet of J-T expansion (high pressure) and the final expansion pressure. This mist settles as liquid in the Dewar. The remaining vapours returns to the suction port of the compressor while passing through heat exchangers. On passing through different heat exchangers it cools the incoming high pressure gas.

All the components operating at temperatures lower than ambient temperature are housed in a stainless steel container called "cold box". In the cold box high vacuum and cryogenic insulation, also called multi layer insulation (MLI) is used to insulate these components thermally from ambient temperature.

Development of Reciprocating Type Cryogenic Expanders

Expanders work on the basic principle of extracting work from the high pressure gas. As the gas is doing external work, it gets cooled. The external work method always produces cooling in comparison to "internal work method", called Joule Thomson expansion. For a gas to cool through a Joule Thomson expansion, it is essential that its temperature should be below a certain temperature, called inversion temperature. For helium gas the inversion temperature is at about 45K. Refrigeration required to cool the gas is produced using two expanders. Expanders can be of two types; turbine type and reciprocating type. Reciprocating type expanders have following distinct advantages over the turbine types: high expansion ratio, low gas flow rate, constant efficiency over wide range of operating conditions, less sensitive to impurities and power fluctuation problems, control of speed/ flow rate is easier. In addition, fabrication of reciprocating type expansion engines is less complicated as compared to turbine type expanders. Although, the turbine type expanders can give better thermodynamic efficiency as compared to reciprocating type, they are suitable for large constant cryogenic load operating over prolonged period.

Table T.1.1: Parameters for 1st Expansion Engine

Diameter: 75 mm, Stroke: 50 mm,
Engine speed: 120 rpm
Inlet cam opening angle: 50 deg
Inlet gas pressure: 17.21 bar absolute,

Inlet Temp., K	Expander Eff., %	Mass flow rate, g/s
300	77	0.22
80	68	0.80
50	64	1.26

Table 1.1.2: Parameters for 2nd Expansion Engine

Diameter: 50 mm, Stroke: 50 mm,
Engine speed: 120 rpm
Inlet cam opening angle: 45 deg,
Inlet gas pressure: 17.21 absolute,

Inlet Temp., K	Expander Eff., %	Mass flow rate, g/s
300	86	0.08
80	81	0.29
25	75	0.92

Fig.T.1.2: Photograph showing expansion engine along with heat exchangers and auxiliary components. 1. Cryogenic Expander, 2. Work extraction mechanism, 3. 1st heat exchanger, 4. Flywheel

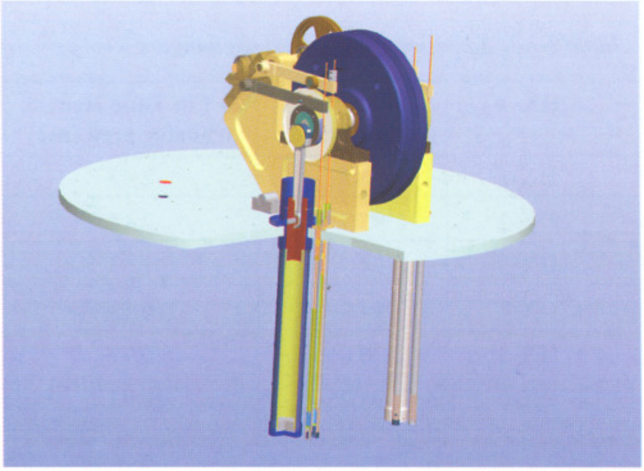

Fig.T.1.4: 3D Model of expansion engine developed at RRCAT

At RRCAT we have developed reciprocating type cryogenic expansion engines to operate at 50K and 20K [2]. Photograph of the system is shown in Fig. T.1.2. Technical parameters of expansion engines developed by RRCAT are given in Table T.1.1 and T.1.2. Expander efficiencies are calculated from experimental data. Both the expansion engines were designed at RRCAT and fabricated by local fabricators. These engines consist of extended length Fibre Reinforced Plastic (FRP) pistons. Low thermal conductivity of FRP and long length results in reduction of heat in-leaks through conduction form room temperature to the expansion space. Heat in-leak through conduction is further reduced by keeping the wall thickness of the expander liner to minimum. This minimum thickness is determined by exhaustive analysis using ANSYS, see Figs. T.1.3 and T.1.5. FRP procured from

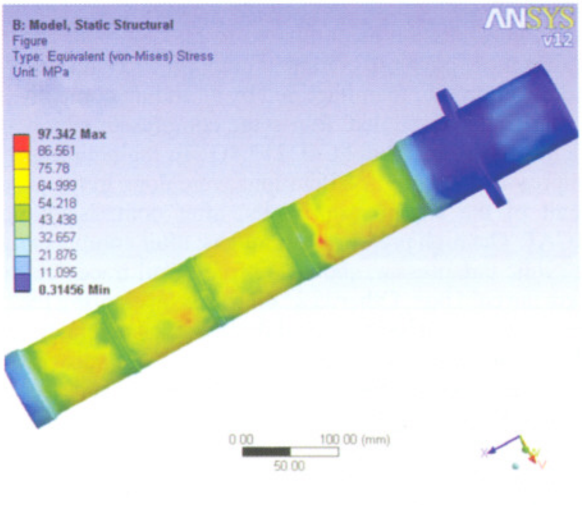

Fig.T.1. 3: Stress analysis of expander liner using ANSYS

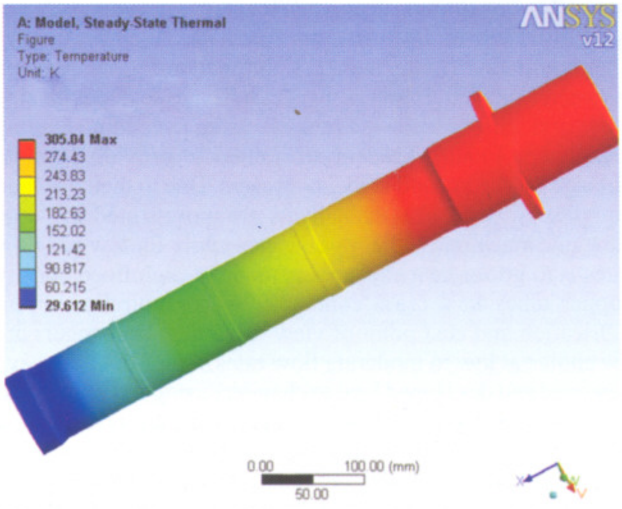

Fig.T.1. 5: Temperature profile using ANSYS analysis

Table T.1.3: Specifications of heat exchangers

HX- #	Efficiency, (%)	Fin Tube Heat transfer area (m2)
HX-1	95.5	2.45
HX-2	95.7	2.14
HX-3	94.7	1.53
HX-4	94.9	0.53
HX-5	96.6	0.72
HX-6	95.7	0.92

local market is used. Due to the extended length, the expansion process takes place deep inside the cold box, whereas other components of expansion engines such as fly wheel, inlet and exhaust valve actuators, work extraction mechanism, etc operate at room temperature. The gap between the piston and expander liner, also called "void volume", plays an important role in achieving the required expansion efficiency. An alternator, used in automobiles, is suitably modified to work as "work extraction device". Design of all the components of expansion engine were finalised using 3D modelling, Fig. T.1.4.

Development of Cryogenic Heat Exchangers

Another crucial part of a helium liquefier is its heat exchangers. In early days people have developed and used different types of heat exchangers. Description of those types is beyond the scope of this article. Now a day's state of the art is counter flow aluminium plate fin heat exchangers. These can offer maximum heat transfer area in unit volume, typically 1300 to 1400 m^2/ m^3. They use high fin density aluminium fins (more than 1.2 fins per mm), sandwiched between claded aluminium sheets. Sides are sealed with side bars and this block is brazed using vacuum brazing techniques. Finally headers are joined to provide separate passage for the hot and cold gas streams. Due to their cost and complexity, these heat exchangers are more suited for large flow rate machines. Other option, especially for low gas flow rates is to go for heat exchangers made of high fined density copper tubes in a cross counter flow configuration. From fabrication and cost point of view these heat exchangers are the choice at low to moderate flow rates. At RRCAT we have designed and developed heat exchangers using integral finned tubes made by an Indian manufacturer [3, 4]. We have used six numbers of cross counter flow type heat exchangers operating between different temperature ranges (300K to 6K). Fig. T.1.6 shows photograph of one of the heat exchanger, developed at RRCAT. Specifications of the heat exchangers used is given in the Table T.1.3. The thermal efficiencies given in the table are calculated from experimental data.

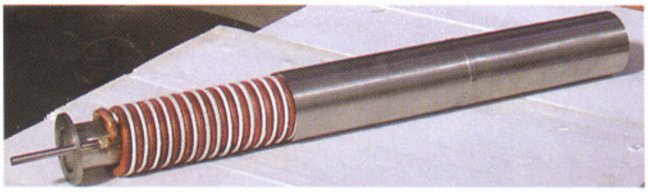

Fig.T.1.6: Photograph of heat exchanger HX-6 before final welding

High pressure helium gas finally cooled to about 7K or lower, with the combination of expansion engine and a train of heat exchangers, enters a Joule Thomson (J-T) expansion valve. On expansion, a part of the flow condenses as liquid. This J-T valve also, was designed and fabricated in house. For providing thermal insulation, all parts of the helium liquefier operating at temperatures lower than ambient temperature, viz. expansion engine, all heat exchangers and Joule Thomson valve are housed in a stainless steel vessel, called "cold box", see Fig. T.1.7. The stainless steel vessel is of approximate dia 1100 mm and height 1500mm. It was fabricated by a local fabricator. Cryogenic insulations also called multilayer insulation is made from locally available materials after characterizing it for liquid helium temperature.

Cyclic Compressor

The next crucial component after expansion device and heat exchangers is the main cyclic compressor. This compressor compresses the low pressure (typically 2 psig) gas to 230 psig. Helium gas being a mono-atomic gas has larger heat of compression as compared to air or Freon, and also requires more power to compress compared to later. We have used a compressor manufactured by an Indian company. It is oil lubricated, air cooled, four stage compressor supplied by M/s Sulzer India, Model C4U217.4G. To maintain purity in compressed helium gas, alterations were done in the process circuit of the compressor by us, after commissioning at RRCAT. The high pressure helium gas, after compressing by the cyclic compressor, should be free of oil traces before it enters the cold box. Otherwise, oil traces on entering the cold area will freeze on inside wall of the heat exchangers. Initially, reducing the heat exchanger efficiencies and subsequently increasing pressure drops. It will also limit the total operation period of the system in a single run before flow passages gets clogged due to solidification of oil. An oil removal system is also designed by us and subsequently fabricated by local fabricators. In addition to its design and fabrication, processing of components used in it plays an important role.

Fig.T.1.7: *Photograph shows Helium Liquefier developed at RRCAT*

Locally available activated charcoal has been used in our system after extensive processing and parameters validation. Standard oil coalescing filters are used in this system.

Process Integration of Components

Fig. T.1.7 shows photograph of helium liquefier developed at RRCAT along with other auxiliary components. A liquid nitrogen cooled external helium purifier, developed by us, is being used to purify the supply of helium gas to the process circuit for liquefaction. The stable operation over long period is ensured using a Helium Gas Control and management system which maintains flow of makeup helium gas, while keeping the operating pressure constant. We could operate the liquefier uninterrupted till the main Dewar, with capacity of 250 liters, was filled up to safe limits. This has been already done for more than two times with repeated performance.

The main hurdles in the development of machinery which can produce cryogenic temperature are an efficient oil removal system, selection of suitable lubricating oil for the cyclic compressor, high efficiency expanders and definitely efficient heat exchangers. Fabrication procedures also need to be developed, such as development of high quality welding and brazing. This plays an important role in the development of cryogenic systems, as one of the regularly faced problems in such development is occurrence of so-called "cold leaks". Processing of different components is another important parameter to achieve acceptable impurities level during operation. Both the processing of components and leaks, take substantial time in the total time taken for development of cryogenic machinery.

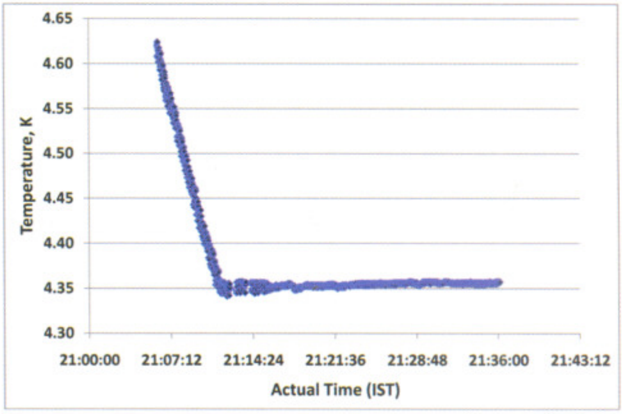

Fig.T.1.8: *Temperature reading of the sensor put inside the liquid helium collection container after J-T valve, when liquefaction was approached for the first time.*

Helium Liquefier Current Operational Status

On August 14, 2010 at 21.15 hrs Helium liquefaction was achieved at 4.35K, 1140 mbar absolute, approx. 2.5 psig, using a completely indigenous system for the first time in the country. Fig. T.1.8 shows temperature reading of the sensor installed inside the liquid helium collection container immediately after J-T valve, when liquefaction was approached for the first time. The system was further modified so that helium is liquefied in an external Dewar. On October 13, 2010 we could collect liquid helium in an external Dewar. During its maiden trial itself, the system was operated for more than 25 hours continuously in liquefaction mode and more than 150 litres of liquid helium was collected in the external Dewar. Liquefaction rate achieved was about 6 lit/hour.

Since then the liquefier has been operated several times. No degradation in its performance has been observed. No oil carry over to cold box is observed. Now temperature sensors are put on several locations to validate the design parameters under refrigeration and liquefaction mode. This will help us to further optimise the system.

Future Plan

Immediate future work is to improve the overall performance of the system and to increase the capacity of this liquefier from its present capacity of 6 lit/hr to about 15 lit/hr. At present LN2 cooled external helium purifier, developed by us, is used for preventing impurities to enter the liquefaction process. Due to operating temperature, this type of purifier has limitation for purifying the helium gas. In this case, impurities although in very small quantity, may limit the reliable operating period of the liquefier to operate it continuously over several weeks. An integral gas purifier which takes care of removing impurities down to 20K with auto regeneration mechanism needs to be designed and added to the circuit. It will use refrigeration produced by the system itself for freezing out the impurities. To make it user friendly an automatic process control for cool down, unattended operation and shut down needs to be incorporated.

Conclusion

A Helium Liquefier has been designed and developed indigenously. Crucial components such as reciprocating type expansion engines, heat exchangers, Joule Thomson valve are designed by us and fabricated locally. Successful operation of the helium liquefier using a local compressor over prolonged period, demonstrates the capability of removing impurities down to a level, which is acceptable for the operation of a liquefier. In particular, processing of different components, such as compressor oil, charcoal beds, as well on-line oil removal technique, has been established. This is often a big hurdle in the smooth operation of cryogenic machinery.

Acknowledgements

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REFERENCES

[1] Barron R F, "Cryogenics systems", 2nd Edn. Oxford university press, UK, 1985.
[2] Rupul Ghosh, R S Doohan, R C Sharma, P K Kush, Indian Journal of Cryogenics, Vol. 35 No. 1-4, p. 258, 2010.
[3] Prabhat Kumar Gupta, P K Kush, Indian Journal of Cryogenics, Vol. 35, p. 437, 2010.
[4] Prabhat Kumar Gupta, Kush P K, Tiwari A, Cryogenics 47 (2007) 322-332.

BIBLIOGRAPHY

Flynn TM, "Cryogenic Engineering", Marcel-Dekkar Inc.(1996)

Steven W Van Sciver, "Helium cryogenics", Plenum Press (1986).

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