CRYO-REFRIGERATORS FOR CNS APPLICATIONS

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1. Summary

Cryo-refrigeration plants for cold neutron sources belong to the field of auxiliary plants or utility facilities of the reactor. In general, they are classified as non-nuclear and serve to dissipate the heat generated in the liquid hydrogen or deuterium from moderating the neutrons of the cold neutron source.

Cryo-refrigeration plants for the temperature range of 20 K supply either refrigeration at constant temperature by means of evaporating the cryogenic coolant (usually hydrogen) or, as usual with cold sources, in a specific temperature range by means of warming-up the cryogenic coolant (usually helium) in the moderator or heat exchanger (condensation or subcooling of the deuterium).

The operator's requirements to a refrigeration plant are, first of all, that the plant adjusts itself - at low-maintenance or maintenance-free - to the various operation modes at best thermodynamic efficiencies and that it offers as much operating convenience and operating safety as possible. Additional requirements are short times for cool-down, capacity adjustment, stand-by operation in order to avoid poisoning of the cold source and further operational requirements. However, these requirements are limited by mechanics, thermodynamics and financial means. For this reason, for each application a technical solution must be found which is optimally adapted to the competing requirements and which is based on a standard product of the manufacturer, if possible.

The operator's different requirements have to be taken in account with regard to the design of the plant and choice of the components; economic aspects in addition also have to be considered. Wherever possible, proven standard components should be used.

For many decades Linde Kryotechnik AG has developed, designed and manufactured helium refrigeration plants for diverse applications like the research reactors FRMII in Garching, KFKI in Budapest and SINQ in Villigen. In the poster presented, the helium refrigeration plants for this applications serve as examples to explain the different operation modes and to present the components used.

2. Basis of refrigeration

As generally known, heat only flows from a place of higher temperature to a place of lower temperature. The refrigeration technology aims at the opposite, i.e. a quantity of heat Q_0 shall be transported from a low temperature level T_0 up to the higher ambient temperature T_U. To reverse a process which works on its own in one direction requires work input. [1]

If the refrigeration process shall take place not only once, but continuously, the heat quantity Q_0 is transformed into the refrigerating capacity Q_0 and the work A into the input power P. [1]

BRAYTON PROCESS[1]

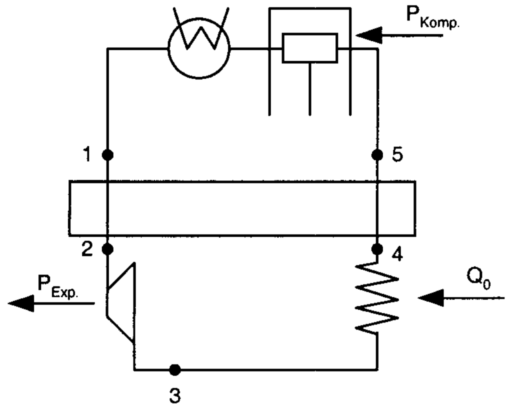

Fig. 1: Flow chart of the Brayton process

The Brayton process constitutes the basic process of all large cryo refrigeration plants. In the ideal case, it consists of

- an isothermal compression at ambient temperature
- a countercurrent heat exchange in which a high-pressure stream is cooled down and a low-pressure stream is warmed up isobar.
- an isentropic expansion with work extraction
- and an isobar release of refrigerating capacity (absorption of heat Q_0).

3. Cryo Refrigerator Process

The process of a helium refrigerator for a CNS application is a typical Brayton cycle and starts with the compression of the helium gas by an oil injected screw compressor from a suction pressure between 1.05 bar and 3.0 bar (dependant on the pressure allowed in the CNS heat exchanger) to a discharge pressure between 8 and 15 bar a. In a second step the oil contained in the compressed helium is removed in the oil removal system consisting of coalescers and a final charcoal adsorber. The pure, high pressure (HP) helium then is discharged to the coldbox for cooling down the helium to the temperature required for the cooling of the CNS.

In the coldbox, a vacuum insulated vessel containing all the cold equipment, the HP helium stream first is cooled in counter current in a heat exchanger by cold returning LP helium. Further cooling of the helium flow is accomplished either by expansion in the turbines or by the LP stream in additional heat exchangers. Finally the helium will be expanded near to the suction pressure of the compressor.

The arrangement of the components within the coldbox strongly depends on the CNS supply conditions required for the helium. In case the pressure of the helium has to be higher than the deuterium pressure, the final expansion will take place after the helium has returned from the CNS, please refer to Fig. 2.

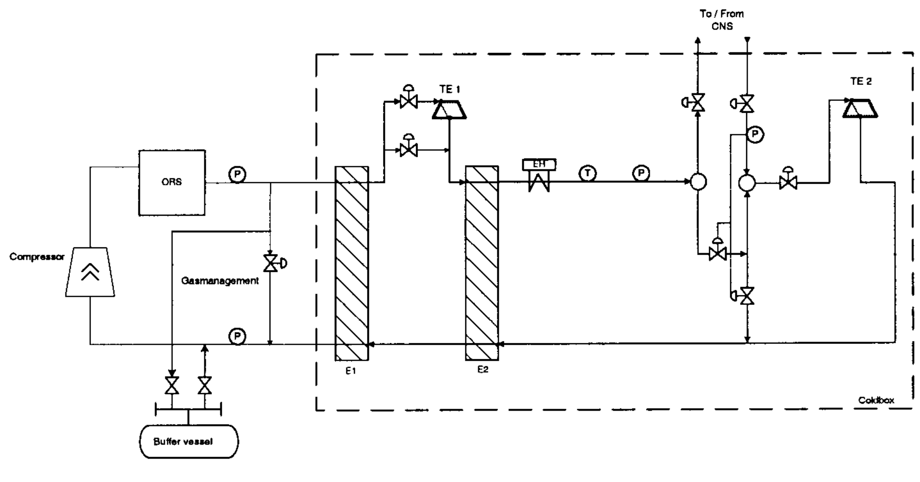

Fig 2: Process flow sheet for D2/H2 at low pressure

If the pressure of the deuterium can be higher than the helium supply pressure the expansion will take place before helium is supplied to the CNS, please refer to Fig. 3.

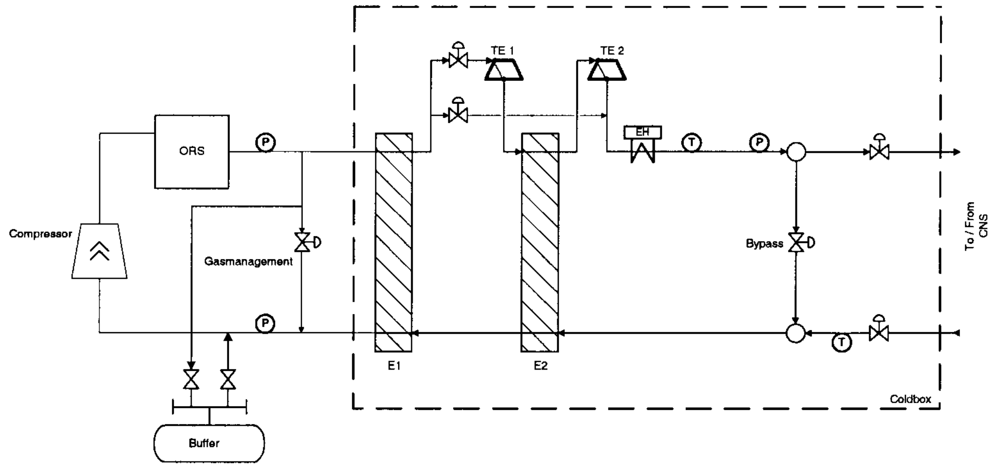

Fig. 3: Process flow sheet for D2/H2 at higher pressure

After cool-down the helium stream will be supplied to the CNS at a constant temperature which is usually 19K with cold sources and warm up by a specific temperature range by picking up the heat in the moderator cell or heat exchanger (condensation or super-cooling of the deuterium). After warm-up the helium gas is returned as LP stream to the coldbox, warmed up in the heat exchangers to ambient temperature and subsequently returned back to the suction side of the cycle compressor.

Load Adaptation

There are different ways to adapt the capacity of a cryo refrigerator to the load changes of the CNS. For small refrigeration plants it is common to use a heater and to run the refrigerator at full capacity since the related savings of electric power input are marginal only.

For larger systems there are several ways to adjust the refrigerator to a load change. One solution would be to run the compressor during full capacity at an elevated (loaded) suction and discharge pressure. If the load in the CNS is reduced the suction pressure and discharge pressure will be decreased too (at constant pressure ratio). As a result the mass flow of the compressor is reduced and subsequently the refrigeration capacity and power input to the system. This solution requires that the pressure allowed in the CNS heat exchanger could be up to 4 bar and varied during operation.

If the pressure allowed in the CNS heat exchanger has to be lower and constant during operation the load adaptation also can be accomplished by using a frequency converter for the electric compressor motor. Reducing the speed of the compressor will decrease the mass flow and subsequently the refrigeration capacity and provides related power savings.

4. Plant Components

Cycle Compressor

Today mainly oil injected screw compressors are used for the compression of the recycled helium stream. Screw compressors are highly reliable at a minimum requirement for maintenance.

Coldbox

The cryo refrigerator coldbox can be either designed as a horizontal or vertical vacuum vessel dependant on the size and space available. Both designs do provide easy access to the internals. The instrument panels required will be mounted directly to the to the vessel or installed adjacent to the coldbox.

The cold box contains all the cold components for the cooldown of the helium like heat exchangers, the guardadsorber, cryogenic valves and piping and the cold part of the turboexpanders. All equipment operating at low temperatures and the inner surface face of the vacuum vessel are covered by a multi-layer of superinsulation to reduce the heat loss by radiation.

A vacuum pump system consisting of a mechanical roughing pump and an oil diffusion pump is connected to the coldbox to maintain the required vacuum.

Heat Exchanger

Brazed aluminum plate-fin heat exchangers are the preferred type of heat exchangers used in state of the art cryo refrigerators, only for very small capacity plants spiral wound tube heat exchangers are an alternative.

The particularly favorable characteristics of plate-fin heat exchangers are:

- small temperature differences between several flow streams
- high flexibility regarding pressure, number and direction of flow streams
- highly compact design with large specific exchange surface (up to 2000 m^3/m^3)
- low pressure drop
- clean fabrication, brazing in vacuum with no need for flux

Plate-fin heat exchangers can be used in the temperature range 1.8 K to 350 K and at pressures up to 75 bar.

Expansion Turbines

The turboexpanders used by Linde in the helium refrigeration plant are small, single-stage centripetal turbines braked by a directly-coupled, single-stage centrifugal compressor. All are equipped with dynamic gas bearings operating at ambient temperature. The maximum operating speeds are between 216'000 to 114'000 rpm. Self-activating gas bearing turbines do not require a separate gas bearing system; the compressor circuit supplies the gas automatically. The Linde helium turboexpanders with gas bearings have successfully logged more than three million hours in installations all over the world.

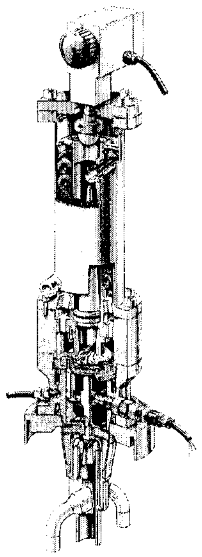

Fig. 4: Linde turboexpander

Main components of the turbine are:

- the turbine housing including the fixed nozzle ring
- the bearing cartridge, containing the bearings, the shaft with the turbine wheel (runner) and the brake compressor (impeller)
- the compressor housing
- the brake cooler with integrated brake valve

Special features:

- simple in construction
- reliable in operation
- requires no scheduled maintenance

Plant Control System

State of the art refrigerators are controlled by use of an industrial process control system and are designed for full unattended operation. The human machine interface is done either locally or remote controlled via a profibus system from the central reactor control station. Linde's remote diagnostics system allows remote access from the Linde's home offices to support operators at site.

5. Requirements to industrial cryoplants

Ambient Condition

Multiple marginal conditions for concept, layout and operation of a cryo refrigerator plant result from a specific site, such as:

- Max/Min. ambient temperatures
- Maximal air humidity
- Availability and conditions/quality of utilities (electricity, air pressure, cooling water, liquid nitrogen)
- Space and load requirements
- Earthquake protection and seismic analysis
- Accessibility during operation and for maintenance
- Impact of magnetic fields or radiation on instrumentation and controls

Codes and Standards

Despite efforts for standardization, big differences between the various national regulations still exist, particularly with regard to

- Design, layout, material, testing and documentation of components and piping subjected to pressure and
- Design, layout, material and testing of electric components particularly for potentially hazardous areas regarding explosions.

6. Safety issues

The significance of safety should not being questioned in any scientific or technical project. For work in the range of very low temperatures, special importance has to be attached to safety. Apart from the normal precautions to be taken, the modifications of the physical properties due to the low temperatures have to be taken into account. Furthermore, at low temperatures, not only differences with regard to the properties at room temperature, but also big changes in the properties within small temperature ranges have to be considered. In order to ensure safe operation at low temperatures, it is essential to know the potential hazards.

Danger of Asphyxiation

As a result of the evaporation of cryogenic liquids, the possibility of oxygen displacement in closed and poorly ventilated rooms exists. As most cryogenic gases are colorless and odorless, this danger is not immediately recognizable. As regards argon and nitrogen, these gases can accumulate near the floor or in the basement, as they are heavier than air. Already a reduced oxygen proportion of 10% unconsciousness

Danger of Overpressure

Helium gas at a temperature of 15 K expands when warming up to room temperature by a factor of 20. For this reason, by the enclosure of cold gas or by increased heat incidence, significant overpressures can arise, which can result in the damage of the internal components, if the gas generated is not being relieved and vented quickly enough.

Danger of Accident and failure induced by Operation

The causes of accident and failure induced by operation include operating errors, the use of wrong or inappropriate equipment, errors of the process control engineering, malfunctions or failure of plant components, failure of safety installations, accidents during transport etc. The possible effects and consequences of accidents induced by operation can be determined and avoided only by a detailed safety analysis. A safe process requires a safe cryo refrigerator plant, which means that the safety aspect have to be taken into account in every step during design, manufacturing, acceptance and operation.

7. Availability

The availability of a cryo refrigerator in a CNS application gains in importance, so that information regarding

- Maintenance intervals (Mean Time Between Maintenance, MTBM),
- Susceptibility to failure (Mean Time Between Failures, MTBF),
- Repair time (Mean Time To Repair, MTTR) and thus
- Availability (ratio of actual time to planned time during which the capacity of the plant is available)

are increasingly required. Individual helium refrigerating plants achieve nowadays an availability of approx. 99% with maintenance intervals of about one year.

Linde Kryotechnik AG has developed a Reliability Data Bank that lists component failure rate data compiled from independent sources as well as information compiled from its own system of operating experiences. This data bank is a valuable source of verifiable failure rate data, both for common process equipment, and for specialized equipment found in Linde Kryotechnik AG facilities.

As an example for the Failure Rate please see the data (data are based on an evaluation time of 66 months) compiled for Linde Kryotechnik AG's gas bearing turbines:

	TGL16	TGL22	TGL32	TGL45
MTBF (h)	250'038	88'917	82'500	142'633

8. Conclusion

For design of such dedicated systems, information exchange between end user of CNS and industry is helpful from the very beginning. This will result in an optimized and special adapted refrigerator, which has to supply 8'000 hrs per year trouble free refrigeration.

9. References

[1] **Quack, H., Prof. Dr.;** "Thermodynamische Grundlagen der Kälteerzeugung"; VDI;