Centrifugal compressors for He circulation loops for ITER

G Kouzmenko1, M Simon1, S Saulquin1, J Buskop2, T Voigt2, D Grillot2, M Ferioli3 Feraille D4

1Fusion for Energy, C/ Josep Pla 2, Torres Diagonal Litoral, 08019 Barcelona, Spain
2ITER Organization, Route de Vinon-sur-Verdon, 13067 St. Paul-lez-Durance, France
3Air Liquide Global E&C Solutions (France), 57 Avenue Carnot, 94500 Champigny-sur-Marne, France
4Expert consultant in cryogenic gases machineries
Grigory.Kouzmenko@f4e.europa.eu

Abstract. Thermal shields of ITER machine and cryopumps are cooled by two forced-flow helium cooling loops using helium at 80 K as a cooling media and liquid nitrogen as a source of cooling. Two-stage integrally geared centrifugal compressors provide mass flow of up to 4 kg/s per each machine with a suction and discharge pressure of 1.6 and 1.8 MPa correspondingly. This is the first in the world use of such machines for helium, and therefore an extensive testing program was developed to demonstrate as much as possible that the required performance is achieved. This paper presents the details of chosen construction of machines, as well as explains particularities of using centrifugal compressors for He and specific problems which were required to be solved, in particular to meet strict leak tightness requirements and overcome rotordynamics issues. Factory testing program and achieved results regarding machines’ performance and treatment of shaft seal leaks are also described.

1. Introduction

The ITER project is an international collaboration between the European Union, China, India, Japan, Korea, the Russian Federation and the USA intended to build a fusion device to demonstrate the feasibility of using fusion power as a source of energy production. ITER is being constructed in Europe, at Cadarache in the south of France.

As superconducting magnets are necessary to confine fusion reaction plasma, the machine requires a large cryogenic system in order to keep magnets in the superconducting state. Other users of the cryogenic system include the cryopumps intended to maintain vacuum in the plasma chamber, the machine’s cryostat and the neutral beam heating system [1].

A large amount of power at 80 K is required for thermal shielding and heat load interception as well as dealing with the regular regeneration cycles of the cryopumps. In order to avoid activation of liquid nitrogen in the heart of the machine (the tokamak), helium is used as a transport media for this power at 80 K. As a result, a large He circulation system is required: the 80 K loops.

For redundancy and maintainability purposes two identical 80 K loops are used. Each 80 K loop consists of a warm compressor ensuring the circulation of helium in the loop, an after-cooler and a perlite-filled cold box integrating cryogenic heat exchangers [2].
This paper describes the construction of warm compressors and problems related to the use of the chosen type of machines for He. The factory tests of compressors and their components and their results are also described.

2. 80 K loops configuration

As described in [2] two identical 80 K loops are used in the ITER cryogenic system. Both loops run in parallel during normal ITER machine operation, when required 80 K loop cooling power is at its maximum. However, during periods with lower heat loads, so called long term maintenance, only one 80 K loop is sufficient to cope with the load and therefore another one can be stopped for the required maintenance to be performed on it. Interconnection of 80 K loops supply and return flows to the users is done within a special valve box (Cryoplant Termination Cold Box, CTCB [3]) downstream the 80 K loops. In order to ensure maximum redundancy, the compressor stations are also interconnected to enable the operation of cold boxes and compressors in any combination.

![Figure 1. Simplified configuration of the 80 K loops and users.](image)

3. Construction of 80 K loop compressors and specific design features

F4E performed an extensive analysis of possible design options for the 80 K loop compressors in preparation for ordering the equipment. As a result of this work, the centrifugal compressor technology was pre-qualified [2]. Air Liquide Global E&C Solutions (France), which supplies the LN2 Plant and Auxiliary Systems including the 80 K loops equipment, proposed integrally geared centrifugal compressors to be used in 80 K loops. The selected vendor for the 80 K Loop Helium compressors is Atlas Copco Energas (Cologne, Germany). Manufacturing and assembly of compressor core units, as well as assembly and packaging of the complete skids (with integration of the driver), were carried out in the vendor workshop in Cologne. These machines have several specific design features, which are briefly described below.

3.1. Operating media and conditions

One of the particularities of the 80 K loop process conditions is that required compression ratio is quite small and in principle it could be achieved in a single-stage machine. However, due to low molecular weight of He, very high impeller rotational speed would be required, which leads to high peripheral speeds and issues with rotordynamics. Therefore two-stage design has been finally adopted to mitigate the above issues. As compression ratio of a single stage is low, no interstage cooling is required, even for He application, and therefore the footprint of the machine is limited. Aluminium alloy (EN AW-7075) is used as raw material for the manufacturing of both machine impellers. This change was done after performing rotordynamic calculations for originally stainless steel impellers. These calculations showed that overhung masses would not allow meeting vibration criteria given in API617, 7th Ed. The aluminium impellers ensure full compliance with API requirements to later and torsional analysis. The features and design parameters of the compressors are summarized in table 1.
3.2. Minimizing He losses

He is quite an expensive as well as relatively rare commodity, to such an extent that global He supply problems are predicted by some researchers if its operational losses continue to be substantial [4]. Therefore, He losses in the process shall be kept to a minimum. To minimize losses in the shaft sealing system (which is usually the main source of losses for this type of machines) the compressors are equipped with tandem bi-directional dry gas seals. The seals are configured in such a way that process leakage can be easily recovered as pure He and He+N2 mixture which is further separated in dedicated recovery system as described in [2].

Table 1. 80 K loop compressors main features and design parameters.

| Feature                  | Value               |
|--------------------------|---------------------|
| Number of stages         | 2                   |
| Gear type                | Integral            |
| Impellers’ mounting      | Opposite on the single pinion shaft |
| Impellers’ material      | Aluminium alloy EN AW-7075 |
| Interstage cooling       | No                  |
| Shaft sealing            | Tandem dry gas seals|
| Inlet pressure           | 1.57 MPa-a          |
| Outlet pressure          | 1.87 MPa-a          |
| Design mass flow rate    | 4.02 kg/s           |

4. Testing program

A comprehensive testing program was developed due to the unique application of this type of compressors for He. It consisted from parts testing, followed by testing of assembled machines.

4.1. Dry face seals

Operational configuration of tandem dry gas seals is shown in figure 2. In this configuration clean He gas from compressor discharge is supplied via port H and at a reduced pressure of ~0.2 MPa-a – via port J. Flow across labyrinth A is pure He recovered in the process. Flow via port I is also pure He at low pressure composed of leak via inboard (process side) dry gas seal B and labyrinth C. This flow is recovered in LHe cryoplants. Flow via port K is He+N2 mixture composed from the He leaking via outboard (drive side) dry gas seal D and N2 barrier gas supplied via port L and leaking across carbon ring E. Therefore, the main purpose of the inboard dry gas seal B, which works at high pressure difference, is to limit He gas losses from 80 K loop process and subsequent energy expenditure on gas re-compression by the compressors of LHe plant. The main purpose of the outboard dry gas seal D, which works at low pressure difference is to minimize He flow into the impure side, which requires its further separation and purification in the dedicated leak treatment system [2]. Besides, in case of failure of one of the seals operation can be continued safely for the process with slightly reduced efficiency until the seal could be replaced.

Tandem dry face seals were first tested on a test bench at a manufacturer’s workshop with He. During these tests leakages across individual seals were tested by means of pressurizing corresponding chambers upstream a seal. As testing configuration was different from the final, dedicated (stricter) acceptance criteria were set forth. Both dry face seals were tested with pressure difference across correspondent to normal operational pressure and maximum operational pressure at an operational rotation speed. The case of design pressure was also tested in standstill condition. The obtained results have fully met the acceptance criteria.
Tandem dry face seals were further assembled in the machines and leak tested in the close to final configuration with supply of He and N2 via ports H, J and L (see figure 2) and measuring leaks flow and composition on ports I and K. It should be noted that the values of flow are not to be directly compared to the ones obtained in the manufacturer’s testing, due to different configurations of seals used in two testing conditions.

Table 3. Results of testing dry face seals in close to final configuration at compressor’s manufacturer workshop.

| Port                      | Expected Min. | Expected Max. | Guaranteed Min. | Guaranteed Max. | Measured Compressor 1 | Measured Compressor 2 |
|---------------------------|---------------|---------------|------------------|-----------------|-----------------------|-----------------------|
| Seal gas (H), Nm³/hr      | 86.4          | 129.5         | 195              |                 | 100                   | 100                   |
| 100% He leak (I), Nm³/hr  | 12.8          | 16.3          | 25.0             |                 | 18.0                  | 19.5                  |
| Secondary seal gas (J), Nm³/hr | 13.5      | 20.1          | 31.0             |                 | 14.0                  | 18.5                  |
| N2/He mixture (K), Nm³/hr | 4.8           | 11.1          | 17.0             |                 | 7.0                   | 3.0                   |
| He content, %             |               |               |                  | 0.3             | 0.7                   |

4.2. IGV actuator

In order to enable control of the compressor in the required wide operational range, it is equipped with variable inlet guide vanes (IGV). Penetration of IGV actuator through the casing is another potential source of leaks. In order to reduce possible leaks, it is equipped with triple O-rings with intermediate chambers allowing verification of absence of leaks in operational conditions. Due to the access restrictions during compressors factory acceptance it was not possible to perform full characterisation of this design, so it will be performed during commissioning and site acceptance of the compressors in Cadarache.

4.3. Leak testing of components

All other components of the compressors with static seals (including casings, aftercoolers, process piping spools, flanges, silencers etc.) were successfully leak tested at the design pressure where possible or by vacuum method with an acceptance criteria of $10^{-6}$ Pa·m³/s. Leak testing of complete assembled compressor systems will be performed during commissioning and site acceptance.
4.4. Compressors performance test

Both compressor trains were assembled in the test bed at Atlas Copco Energas with corresponding auxiliary equipment including electric motors and aftercoolers and their performance were tested in full operational configuration in closed loop running with He for the guaranteed design case and a further nine operational cases (see figure 3). For the design case the shaft power was guaranteed at 655.9 kW and both machines were running at 2.2 – 2.4% below this guaranteed power. All other parameters (temperatures, pressures, levels of vibrations, etc.) were also within the acceptable limits.

![Figure 3](image)

**Figure 3.** Examples of the results obtained during factory acceptance testing of 80 K loop compressors: performance map pressure vs flow (a) and power vs flow (b) for the design point, characteristic curves isentropic efficiency vs flow (c) and energy head vs flow (d).

5. Current equipment status

Both 80 K loop compressors were manufactured and factory tested by Atlas Copco Energas in Cologne, Germany. Following the factory acceptance the compressors were delivered to the ITER site in the beginning of 2018. The installation of the equipment is ongoing and its on-site commissioning is planned for the beginning of 2019 following the installation and acceptance of interconnecting piping.

6. Conclusion

Following extensive design studies, 80 K loop compressors were designed and manufactured in full compliance with stringent ITER requirements. Performed factory acceptance tests demonstrated that the required performance and leak tightness of the equipment has been met.

7. References

[1] Monneret E, Benkheira L, Fauve E, Henry D, Voigt T, Badgujar S, Chang H-S, Vincent G, Forgeas A and Navion-Maillot N 2017 ITER cryoplant final design and construction *IOP Conf. Series: Materials Science and Engineering* **171**

[2] Simon M at al 2016 Design of the 80 K helium circulation loops for ITER *Proc. 1st IIR Int. Conf. of Cryogenics and Refrigeration Technology* (Bucharest)

[3] Chang H-S at al 2017 Status of the ITER Cryodistribution *IOP Conf. Series: Materials Science and Engineering* **278**

[4] Bradshaw A M and Hamacher T 2013 Nuclear fusion and the helium supply problem, *Fusion Eng. and Design* **88** issue 9–10 pp 2694–97