Cooling scheme for W7-X divertor cryo-vacuum pumps

Chandra Prakash Dhard, Sylvio Raatz

Max-Planck-Institut fuer Plasmaphysik, Greifswald Branch, Euratom Association, Wendelsteinstrasse 1, D-17491 Germany

Ten pieces of divertor cryo-vacuum pumps (CVP) will be installed in the plasma vessel of Wendelstein 7-X stellarator. The inner part of CVP is used for condensation of hydrogen, deuterium etc. and chevrons are used to protect the inner part from the radiation and gas loads. The inner part is cooled with cold helium (He) and operated at 3.4 K and 3.9 K during peak power and standard modes of operation. The chevrons are operated at 80 K and supplied with liquid Nitrogen (LN2). Three different Helium cooling schemes were worked out using forced flow supercritical helium, namely, parallel flow, parallel flow with intermediate sub-cooling and series flow with intermediate sub-cooling. For the chevrons, three cooling schemes i.e. bath cooling, forced flow two phase and single phase with pump, were worked out. The analysis involved the process calculations and thermo-hydraulic calculations considering the operational requirements of CVP. The optimisation was also coupled with the LN2 heat exchangers of the helium refrigerator to find the optimum flow scheme. The regeneration of inner part up to LN2 temperatures and the complete CVP up to ambient conditions is foreseen without affecting the other cooling applications connected to refrigerator.

Keywords: Wendelstein 7-X; Divertor; Cryo-vacuum pump; Cryogenic; Cooling scheme

1. Introduction

The Wendelstein 7-X (W7-X) is a stellarator based fusion experiment designed for steady-state operation. It is constructed with 10 identical half modules, the divertor chamber of each half module is equipped with a CVP for density control of the plasma by pumping, hydrogen, deuterium and helium. The CVP's are located alternatively in the upper and lower part of plasma vessel along the torus. Each CVP is split in two units, i.e. DCU1 and DCU2 which are connected in series by an LN2-shielded cryo transfer line. A further transfer line leads from DCU1 to the port feed through (see figure 1).The CVP comprises of He panel, LN2 chevron, water chevron and the reflector (see figure 2). Water cooled chevron protects the CVP from the high temperature plasma radiation. The LN2 cooled chevron reduces the radiation as well as gas conduction loads at the He panel.

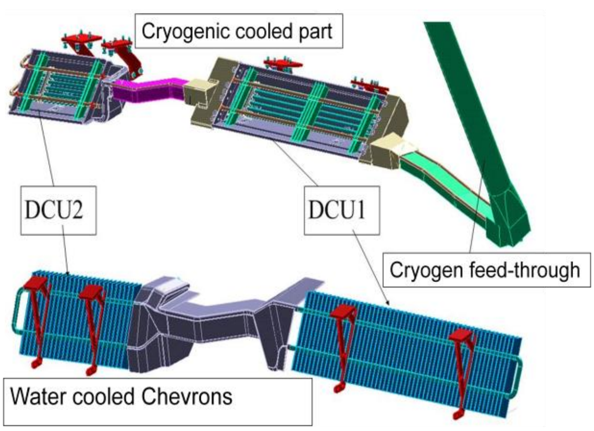

Fig.1 Layout of CVP consisting of DCU1 & DCU2

The design and manufacturing of the CVP's used for W7-X is based on the similar pumps used for ASDEX-Upgrade machine [1]. Ten CVPs are designed for a total ambient hydrogen particle flux of 200 mbar l/s. All its components are made from austenitic steel (sheets 1.4429, tubes 1.4435). For all the 10 CVP's together, the ideal pumping speed is 120 m^3/s in front of the LN2 chevron and 75 m^3/s in front of the water chevron [2].

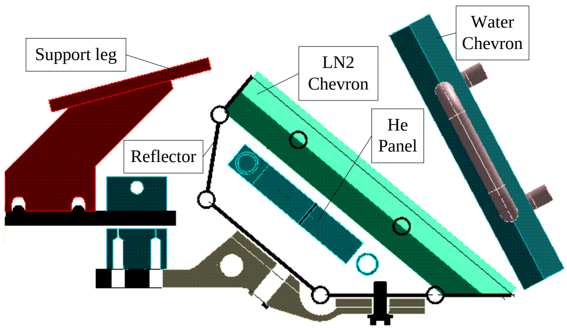

Fig.2 Main components of a CVP

2. Cooling schemes

2.1 Helium panel cooling

The cooling requirements of CVP's are provided by the same He refrigerator planned for other applications of W7-X, i.e. coils, casings, supports, shield and current leads. In order to achieve a good heat transfer and flow stability, it was preferred to provide the cooling with forced flow supercritical helium (SHe) with the pressure > 3 bar(a).

author's email: dhard@ipp.mpg.de

Following three cooling schemes were worked out for He panel cooling:

I. Parallel flow

II. Parallel flow with intermediate sub-cooling

III. Series flow with sub-cooling

For the parallel flow cooling (see figure 3), SHe drawn from the refrigerator is fed to all the CVP's in parallel. A total flow of 250 g/s is necessary to keep the maximum operating temperatures within the limits for various modes of operations. Supply temperatures of 3.4 K and 3.9 K are provided by the refrigerator during peak power mode (PPM) and standard mode (SM) respectively. However due to long distance i.e. ~80 m between the CVP installations and the refrigerator and connections to various armatures such as valves, vacuum barriers, instrumentations etc. the supply temperatures are increased by about 100 mK. Correspondingly the operating temperature of CVP also gets increased.

For the normal operations where hydrogen / deuterium pumping is necessary the achieved temperatures are close to maximum operating conditions, though for the effective helium pumping with Argon frosting, the temperatures need to be further reduced. This can be achieved by providing a sub-cooled liquid helium (LHe) bath close to the CVP. By adjusting the operating pressure of the bath, the required inlet temperature to CVP can be obtained. This option of parallel flow with intermediate sub-cooling gives the flexibility of operating the CVP at predefined temperatures. However in order to gain the flexibility, additional hardware i.e. LHe bath, pumping device to maintain the pressures in sub-atmospheric range, heat exchangers, control equipments etc. need to be provided.

The cooling can be further improved by connecting the two CVP's in series with an intermediate heat exchanger immersed within the LHe bath. This option with series cooling and intermediate sub-cooling provides an additional advantage of reducing the required mass flow rate. Reduced mass flow and correspondingly the reduction in pressure drop helps in reducing the heat load exerted by cold circulator (CC). The flexibility of adjusting the LHe bath pressure could also be exploited to achieve the required operating temperatures (see table 1).

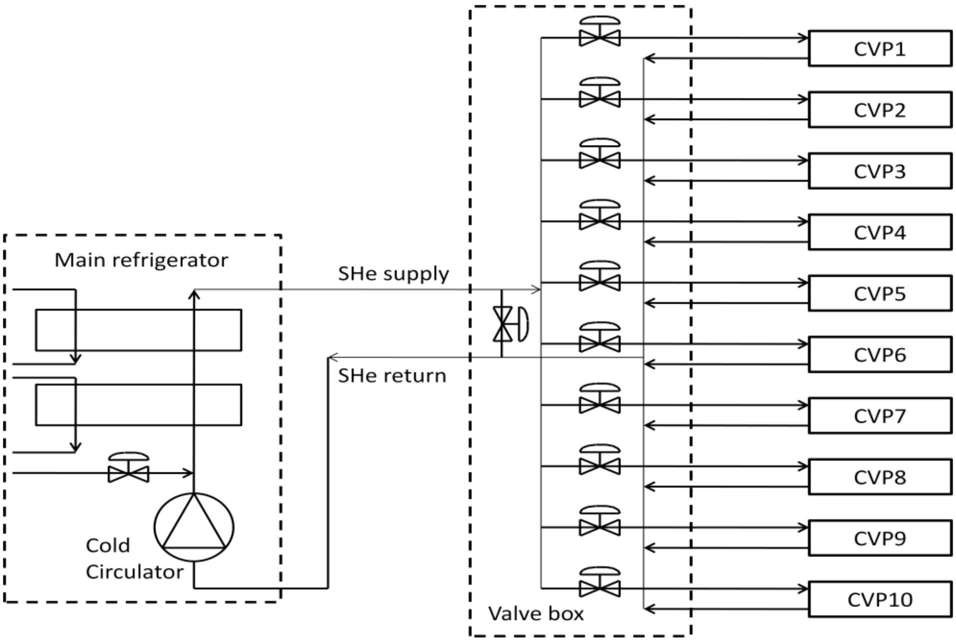

Fig.3 He panel cooling scheme with parallel supply of SHe

Out of these three cooling scheme, even though the third scheme provides the flexibility of operations with adjustable temperatures, because of several critical hardware and control operation requirements, presently it has been decided to postpone this cooling option. In the beginning phase of CVP operations, they will be

Table 1: Process parameters i.e. inlet temperature (T_{in}), mass flow ($\dot{m}$), pressure drop (ΔP) and heat loads for He circuits

Parameters	Parallel flow	Parallel & sub-cooling	Series & sub-cooling
T_{in} (K)	3.5	3.3	3.0
ΔP (bar)	0.6	0.6	0.2
$\dot{m}$ (g/s)	250	250	125
CVP load (W)	450	450	450
CC load (W)	240	240	85

operated with parallel cooling scheme. Within the refrigerator an independent cooling circuit with a dedicated cold circulator has been provided [3].

2.2 Nitrogen Chevron cooling

Following 3 cooling schemes were worked out for nitrogen chevron cooling:

I. Bath cooling

II. 2-phase cooling

III. 1-phase cooling using cold circulator

For the bath cooling, LN2 is withdrawn from the LN2 storage tank (30000 l capacity) located about 100 m away from the CVP installations, and fed to all the 10 CVP's in parallel via a control valve. The return lines are connected to a common bath positioned on the top and the LN2 level is maintained to a constant level within the bath by regulating the control valve.

2-phase cooling is achieved by feeding the sub-cooled single phase LN2 to the CVP's. The LN2 withdrawn from the tank is taken through a heat exchanger immersed within an LN2 vessel. The 2-phase nitrogen returning from CVP's is phase separated within the same LN2 vessel. The LN2 level within the vessel is regulated by the amount of LN2 returned from CVP's.

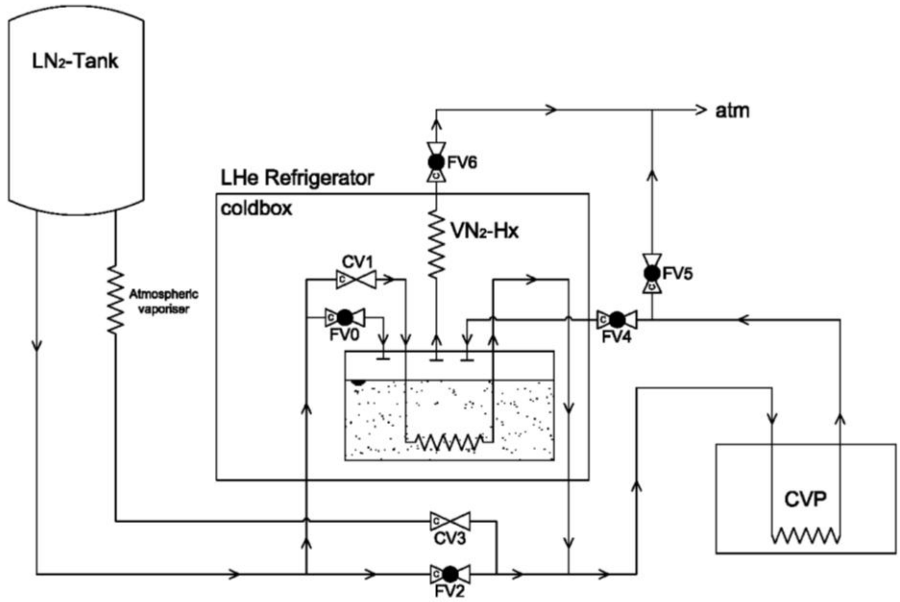

Fig.4 2-phase LN2 cooling scheme of CVP.

1-phase cooling requires the use of LN2 cold circulator within a closed circuit. Cold circulator flows the subcooled LN2 through the circuit, the heat of compression across the circulator as well as the heat load from CVP is transferred to the LN2 bath via the heat exchanger. The limit of outlet temperature at CVP is achieved by adjusting the mass flow rate. This temperature also limits the operating pressures of the circulator in order to avoid falling in the 2-phase regime.

The calculated parameters for all the above three cooling schemes are listed in table 2. For the bath cooling even though the flow requirements are the smallest, but in practice this scheme is suitable for simple volumes and smallest supply pressures from LN2 tank. Higher supply pressure of W7-X LN2 tank i.e. 8 bar raises the saturation temperatures of LN2 and correspondingly the operating temperatures of CVP. Higher supply pressures, narrow LN2 channels and unavailability of space for additional bath at top do not favor this scheme.

Table 2: Process parameters i.e. inlet/outlet temperature (T_{in} / T_{out}), inlet/outlet pressure (P_{in} / P_{out}), mass flow ($\dot{m}$) and heat loads for nitrogen cooling options

Parameters	Bath cooling	2-phase cooling	1-phase cooling
P_{in} (bar)	1.1	1.15	3.35
T_{in} (K)	78	78.4	78
P_{out} (bar)	1.1	1.08	3.25
T_{out} (K)	78	78.4	88
$\dot{m}$ (g/s)	30.01	32.9	300
Heat load (W)	6000	6000	6000

The 1-phase operation requiring usage of circulator provides a very good flow stability however it operates the CVP's at rather higher temperatures, with a high mass flow rate. The arrangements for the installations, controls and maintenance of cold circulator lead to additional implications in terms of cost and reliability of operation.

2-phase scheme as shown in figure 4, provides the minimum operating temperatures with the low mass flow rates. Moreover LN2 sub-cooler / phase separator bath can be coupled with the similar bath needed within the main refrigerator. Therefore this seems a favorable solution.

3. Operating modes

The main operating modes are; long standby mode (LSM), short standby mode (SSM), standard mode (SM) and peak power mode (PPM).

The important feature provided in the refrigerator is a dedicated circuit for operation and regeneration of CVP's at 80K as well as 300K while keeping all the other applications e.g. coils, leads etc. at low temperatures. For regeneration up to 80K, helium panels are warmed up to 80K while keeping the LN2 chevron in operation. However for regeneration up to 300K, helium panels as well as LN2 chevrons are warmed up simultaneously. The warm-up is achieved in a controlled manner, by mixing the warm He and N2 gases to SHe and LN2 flows to He panels and chevrons respectively. The warm-up rate is kept within 100 K/h and the temperature difference across the CVP is restricted to 40 K. After the regeneration, the cool-down is achieved by mixing the flows as mentioned for the warm-up. It is planned to carry out this operation when the other applications are cooled in SSM.

4. Specification of Cryogenic systems

Besides the helium refrigerator which is under commissioning, the cooling system for CVP requires following additional components:

I. Main transfer line

II. Valve box

III. Distribution transfer lines (10 pieces)

IV. Instrumentations & controls

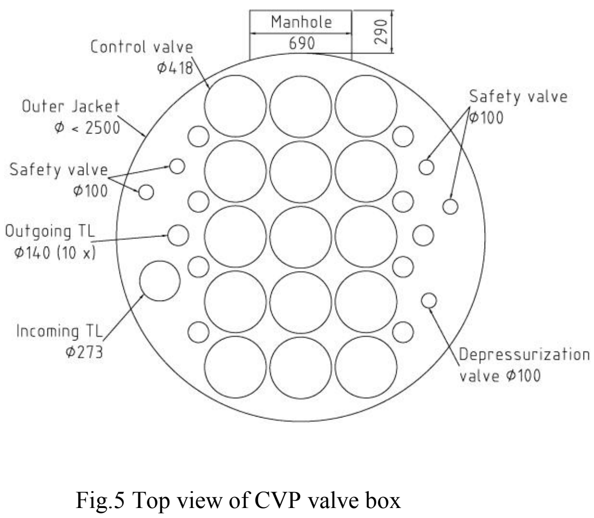

Fig.5 Top view of CVP valve box

The main transfer line connects the refrigerator subcooler box to the valve box (VB). This is about 60 m long vacuum insulated line containing 2 SHe lines and 2 LN2 lines. The main transfer line (TL) is terminated at the VB, kept in the second basement below the torus hall. It is tentatively a cylindrical vessel of diameter of about 2.5 m and height of about 2.35 m (see figure 5). The configuration of vessel could be horizontal or vertical and the exact dimension depends upon the layout of components installed on it. Besides the incoming main TL, the VB top flange contains 10 outgoing TL, 10 control valves, safety valves and depressurization valves. The main TL is terminated with a vacuum barrier however the distribution TL have the common vacuum space with the VB.

The distribution TL, connect VB to CVP's. Each CVP is connected individually with the VB, therefore there are 10 pieces of these lines. Since 5 CVP's are located on the top side and 5 on the bottom side of plasma vessel, the corresponding ports for the TL are also located accordingly. Therefore 5 of these lines are about 20 m long and the remaining 5 are 10 m long. Each line is provided with a vacuum barrier at the port at torus port.

The pressure, temperature and flow measurements devices will be mounted on the piping housed within the VB. The cables will be taken out of VB via vacuum feed-throughs. The controlling of valves will be carried out by a control program based on the signals acquired from the instrumentations.

5. Conclusions

The cooling schemes for helium panels as well as LN2 chevrons for divertor cryo vacuum pumps have been worked out. The helium panels will be cooled with supercritical helium with inlet temperature depending upon the mode of operation. The total helium flow of 250 g/s is distributed in parallel to all the 10 CVP's. The necessity of sub-cooling the helium will be evaluated at later stage after gaining the first hand operational experience. The LN2 chevrons will be cooled by 2-phase LN2 where the cooling circuit is coupled with the refrigerator.

References

[1] B. Streibl et al, Fusion Eng. and Design **56-57**, 867 (2001) and references therein.

[2] S. Benhard et al, Fusion Eng. and Design **75-79**, 463 (2005)

[3] A. Kuendig et al, Proceedings of Twentieth International Cryogenic Engineering Conference (ICEC 20), Beijing, Published by Elsevier Ltd. 2005, p. 51