SUMMARIZED RESULTS OF THE CRYOSORPTION PANEL TEST PROGRAMME FOR THE ITER CRYOPUMPING SYSTEM

CHR. DAY(1), H. HAAS(1), N.T. KAZAKOVSKY(2), A. MACK(1), D.K. MURDOCH(3), D. RÖHRIG(4), G.L. SAKSAGANSKY(5)
(1) Forschungszentrum Karlsruhe, Hauptabteilung Ingenieurtechnik, PO Box 3640, 76021 Karlsruhe, Germany
(2) RFNC-All-Russian Research Inst. of Experimental Physics (VNIIEF), Sarov, Russia
(3) NET Team, Max-Planck Inst. für Plasmaphysik, Garching, Germany
(4) Forschungszentrum Karlsruhe, Projekt Kernfusion, Karlsruhe, Germany
(5) D.V. Efremov Scientific Research Inst. of Electrophysical Apparatus (NIIEFA), St. Petersburg, Russia

Abstract

A reliable but versatile primary cryopumping system is required for high vacuum pumping of the ITER torus during all phases of plasma operation. To achieve that goal, an extensive R&D programme has been performed within the framework of the Nuclear Fusion Project of FZK, supported by the European Communities under the European Fusion Technology Programme. The present paper covers that part of the programme, which focuses on the pumping speed of the recommended cryopanel type and the various aspects of the charcoal-bonding system in the cryogenic temperature range. It is demonstrated that the investigated cryosorption panels exhibit a very good behaviour with respect to pumping efficiency, long-term thermomechanical endurance and compatibility with tritium. The recommended cryopump design was therefore chosen as point design for ITER.

1. INTRODUCTION

The ITER primary vacuum pumping system consists of 16 identical batch-regenerating cryopumps. To guarantee for sufficient helium and protium pumping, the cryopumps are based on cryosorption (combined sorption and condensation) by using cryopanels, which are coated with activated charcoal as sorbent material, cooled to about 5 K. Preparatory tests were run in the past to find an optimum combination of sorbent type and bonding cement, resulting in a ~ 1 mm thick layer of activated charcoal (type CHEMVIRON SC-II), bonded by an inorganic cement. Based on this optimum panel set-up, an essential testing programme has been performed at Forschungszentrum Karlsruhe (FZK) to determine the performance characteristics and to assess the suitability and effectiveness of the cryosorption panel design. All of the FZK tests were made using a full-size ITER panel mock-up in quilted design [1]. As part of a collaboration with the RF hometeam, the compatibility with tritium was investigated. All test panels were coated using a special spray technique developed at FZK [2].

2. DETERMINATION OF DYNAMIC PUMPING CHARACTERISTICS

The pumping speed of a cryosorption pump for a certain gas mixture depends in a very complex manner on the complete pumping history, e.g. the time scale, the arrival rate of the gas, the capture probability and the gas load. As the pumping process is due to two different, but interdependent physical mechanisms (sorption and condensation), the main objective of the test campaign was not only to measure the pumping speed performance at a parametric variation of gas composition, but also to determine and assign the major factors affecting cryopump performance.

2.1. Physical pumping mechanisms

It could be shown that all gases admitted into the pump, while the panels are cooled at 5 K standard operation temperature, are basically pumped by condensation except for helium and protium [1]. This results in a different thermal release behaviour of the gases during regeneration. As the sorption capacity at the partial regeneration temperature of 85 K is still very high for the impurity gases (but negligible for the hydrogens and helium), they will adhere to and accumulate on the charcoal [3].

2.2. Ultimate base pressure

According to the ITER requirements, an ultimate base pressure of 10^{-5} Pa for the hydrogens and 10^{-7} Pa for impurities is specified. Depending on the pumping mechanism, the achievable ultimate base pressure is determined by the sorption or condensation isotherms, respectively at panel operation temperature under vacuum conditions. In that respect, the most critical gases are the hydrogens and helium, which exhibit the highest sorption equilibrium pressures. The measurement results at an approximate charcoal temperature of about 6.5 K are shown in Fig. 1. The shape of the sorption isotherms fully agrees with what is expected from the pore size characterisation of the charcoal type [4]. The achievable base pressure for a pure helium background is limited to the 10^{-6} Pa range.

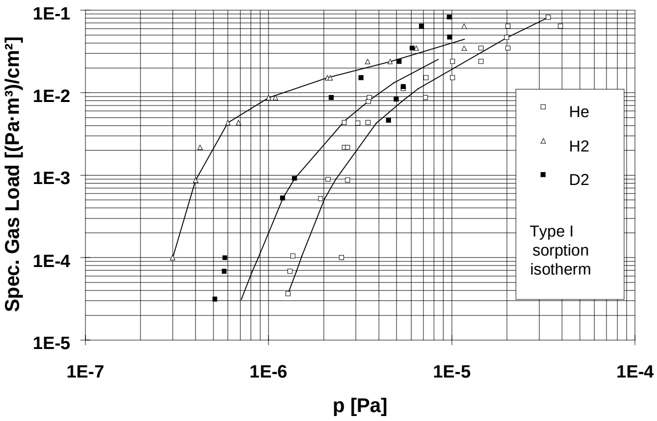

FIG. 1. Sorption isotherms at about 6.5 K.

2.3. Pumping performance

2.3.1. Pure gases

The pumping characteristics with respect to pressure and gas load have been investigated by a parametric variation of the flow rate of the gas to be pumped. For all gases, except He, the maximum ITER gas load on the panels is below the saturation capacity by at least one order of magnitude. A sticking probability of almost unity was measured for D_2 and about 0.9 for H_2, both of which are pumped by sorption. This corresponds to specific pumping speeds (related to the cryopanel area, referenced to 0°C) between 3 $L/(s\cdot cm^2)$ and 3.5 $L/(s\cdot cm^2)$, depending on flow rate and pressure range. The pumping speed for He depends significantly on the gas load and the temperature of the sorbent. The initial He sticking probability (i.e. at zero gas load) varies approximately linearly between 0.64 at 6 K and 0.17 at 7.5 K. In this respect, it must be considered that the actual temperature results from the energy balance of the pumped gas flow and the coolant situation inside the panel channels. In component tests, it was found that for the maximum ITER typical surface-related flow under LHe-cooling conditions, an elevated sorbent temperature of about 7 K must be taken into account. However, for the hydrogens, the panel temperature does not start to exert an influence below 10 K [5].

2.3.2. Mixtures

In this test section, the gas mixtures, which were designed to stand as model gases for the fusion exhaust, were varied systematically in a wide composition range (in terms of typical fractions such as inert gases Ne, Ar, N_2, impurities and He besides the hydrogens as major component). In the first experimental stage, single cycle pumping speed tests were performed to gain a fundamental understanding. As the exhaust gas impurity fractions will accumulate on the panel within the developed partial regeneration concept [3], multi-cycle tests were made in addition, in order to study potential poisoning phenomena (clogging of the pore system). Within the latter tests, the gas flow was kept constant at the ITER value of 2.6 $(Pa\cdot m^3)/(s\cdot m^2)$ to simulate closely the ITER conditions. The main results of the tests can be summarized as follows.

For He-free mixtures, the pumping speed stays almost constant during the whole pumping time and the saturation limit of the charcoal is not reached. The deteriorating influence of the inert gases on the pumping speed is not critical. Fig. 2 (left) illustrates the influence of He content for D_2-based mixtures (D2-Base is a premixed gas consisting of 96 % D_2 and 4 % impurities), composition indicated in mol%. The maximum He content for ITER is about 10%. Even a doubled He content leads to pumping speeds compatible with the ITER requirement for 1 L/(s·cm^2). It should be pointed out that the saturation capacity is very much the same for all helium containing mixtures of interest. This is a very important feature with respect to the inherent safety concept of a limited tritium inventory [6].

Multi-cycle tests yielded only a moderate pumping speed decrease over the cycles and no impact at all for He-free mixtures. The most critical composition was a combination of high H_2 and high He contents. This is due to a competitive sorption situation. However, such a gas mixture is, if at all, only present in the H_2-shot operation mode, which is not the point design for ITER. The experimental results for the various mixtures investigated are given in Fig. 2 (right), which illustrates the general decrease of pumping speed as a function of the number of subsequent pump cycles without reactivation. It is shown that the decrease in speed is not uniform, but exhibits certain recovery effects.

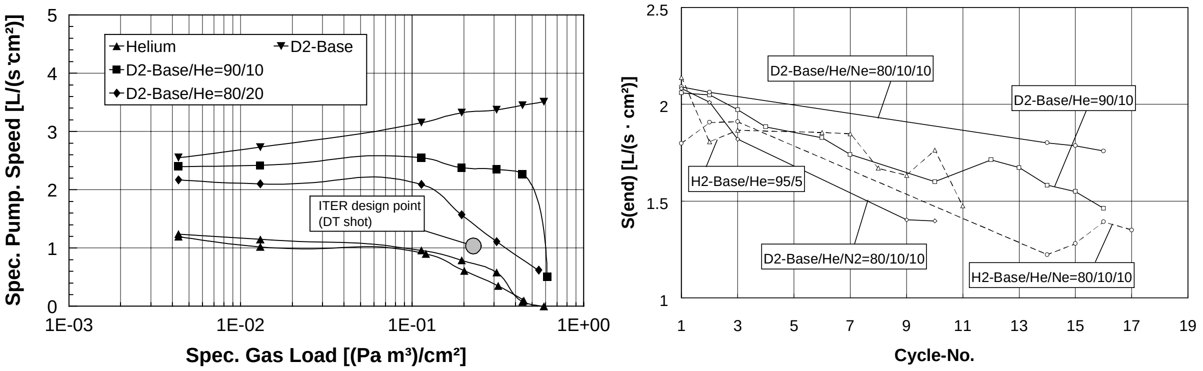

FIG. 2. Pumping speed performance for gas mixtures. Left: Pumping speed curves of D_2-based mixtures vs. gas load; right: Decrease in pumping speed with increasing cycle-no due to poisoning.

To understand the competitive sorption performance in more detail, a special high resolution gas mass spectrometric system was procured, with which we could monitor the composition changes during pumping. A strong relative helium enrichment due to the different pumping speeds of helium and the hydrogens was revealed. It generally turned out that the He enrichment is a quite sensitive characteristic and very well suited to categorise the complex mixture behaviour.

However, all ITER pumping speed requirements can very well be met including a considerable safety margin, which even allows for the 20 % excursion required in the ITER specification.

3. THERMAL CYCLING TESTS

The pumping panels to be used in the ITER primary vacuum pump must be designed to withstand temperature cycling within partial regeneration (5 K ↔ 90 K, about 220 000 cycles for the projected lifetime of ITER) and total regeneration (5 K ↔ 300 K). Even a less frequent cycling up to 100 °C may be necessary to get rid of the accumulated water-like substances [6]. Safety considerations necessitate a large number of time-limited, rapid cycles, which is much more demanding than in any other related application. Therefore, long-term cycling tests for the recommended combination of stainless steel substrate, bonding agent and activated charcol were performed in parallel in two test facilities at different temperature ranges, see Table I. The heating was always established by circulation of warm gas at elevated pressure through the cooling channels, which corresponds to the heating technique anticipated for ITER. The quality of sorbent survival was benchmarked several times during the test programme by the nitrogen and helium adsorption behaviour, respectively. No deterioration or sorbent degradation was detected. In a supporting theoretical analysis based on two dimensional Finite Element Modelling of the substrate/bonding complex it was shown that the internal pressure cycling between pumping and heating is the decisive factor for the lifetime of the panel.

TABLE I. PARAMETERS CHOSEN FOR THE THERMAL CYCLING TESTS.

Feature	Cycling 5 K ↔ 100 K	Cycling 100 K ↔ 300 K
No. of cycles	7 000	10 000
Cycle time (cooling + heating)	75 s / 5 s	2 min / 3 min
Heating medium	gaseous He (300 K, 1.5 MPa)	gaseous N_2 (300 K, 1 MPa)
Coolant medium	supercritical He (4 K, 0.5 MPa)	liquid N_2 (0.15 MPa)
Total detached charcoal*	0.53 g (0.2 % of all)	0.89 g (0.5 % of all)
Validation	He pumping speed	N_2 sorption capacity
Optical inspection	no degradation visible	no degradation visible

* Most of the loss occured early in the test campaign, with the loss rate subsequently stabilising at a very low level.

4. IMPACT OF TRITIUM ON THE CRYOSORPTION PANEL

The goal of this test campaign was to demonstrate the resistance of the recommended panel set-up to tritium [7]. The panels were exposed to tritium at 78 K (exposure in the order of 10^{10} Pa·s, which is roughly corresponding to the ITER lifetime). Before and after tritium exposure, the sorption capacity for D_2 at 78 K was determined for comparison. A small decrease in sorption capacity (within the limits of measurement error) was reproducibly measured; however, the deterioration effect is comparatively moderate. It was also observed that tritium accumulation is less than proportional to exposure (expressed in terms of the product pressure x time). The panels were then regenerated at 78 K and at 300 K for detritiation. The amount of residual tritium depended strongly on the chosen regeneration temperature (factor 8 between 78 and 298 K), but not significantly on the duration of regeneration, where a saturation seemed to be attained after about 0.5 h. To validate the strength of charcoal bonding after tritium exposure, thermal cycling tests were performed, comprising 100 cycles between 78 K and room temperature and between 78 K and 423 K, respectively. After these tests, no relevant mass loss was detected; X ray phase analysis revealed that the cement microstructure also remained unchanged.

5. CONCLUSION AND OUTLOOK

The R&D results achieved within the panel test programme firmly support the panel set-up, which is recommended for ITER and chosen as point design in the ITER Final Design Report. The panel type is installed in the ITER model pump to be tested at FZK. The poisoning influence of high-boiling substances with a strong sorption capacity (such as water or higher hydrocarbons) will be determined in parallel in the very near future. It is proposed to continue the investigation of the tritium effect at the RF hometeam especially in the temperature range of 5 K. The investigation of the charcoal microstructure has already started. Additional tests are also prepared at the Tritium Lab of FZK.

REFERENCES

[1] DAY, CHR., MACK, A., "Investigation into pumping characteristics of ITER cryopumps", Fusion Engng. Design **39/40** (1998) 955-962.
[2] HORN, S., KAMMERER, B., Deutsches Patent Nr. 4041725 (1995).
[3] DAY, CHR. et al., "The experimental basis for the ITER cryopump regeneration concept", Proc. 20th SOFT, Marseille, France (1998) 921-924.
[4] GREGG, S.J., SING, K.S.W., Adsorption, surface area and porosity, Acad. Press, London (1982)
[5] DAY, CHR. et al., "Pumping performance of cryopanels coated with activated carbon", Adv. Cryogenic Engng. **43** (1998) 1327-1334.
[6] MURDOCH, D.K. et al., "Tritium inventory issues for future reactors; choices, parameters, limits", (Proc. 20th SOFT, Marseilles, France, 1998), to be published in Fusion Engng. Design.
[7] KAZAKOVSKY, N.T. et al., "New results of model cryosorption panels for ITER vacuum pump tests in tritium", Proc. 20th SOFT, Marseille, France (1998) 1029-1032.