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Large-Scale Cryopumping for Controlled Fusion*

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ABSTRACT

Vacuum pumping by freezing out or otherwise immobilizing the pumped gas is an old concept. In several plasma physics experiments for controlled fusion research, cryopumping has been used to provide clean, ultrahigh vacua. Present day fusion research devices, which rely almost universally upon neutral beams for heating, are high gas throughput systems, the pumping of which is best accomplished by cryopumping in the high mass-flow, moderate-to-high vacuum regime.

Cryopumping systems have been developed for neutral beam injection systems on several fusion experiments (NIXT, IFIR) and are being developed for the overall pumping of a large, high-throughput mirror containment experiment (MFF). In operation, these large cryopumps will require periodic defrosting, some schemes for which are discussed, along with other operational considerations.

The development of cryosources for fusion reactors is begun with the IFIR and MFF systems. Likely paths for necessary further development for power-producing reactors are also discussed.

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Introduction

Cryogenics has always been an important part of fusion research technology. The necessity of cryogenically-cooled superconducting magnets for fusion reactors is well recognized.

Fusion research requires the attainment and maintenance of high vacuums, since cold background gas and the presence of impurities are highly unfavorable to the maintenance of high temperature plasma. Historically, cryogenics has played an important part in the development of vacuum technology and vice-versa.

In the fusion experiments being built today, vacuum pumping requirements are such that conventional appendage pumps (diffusion, ionization, cryo-) simply cannot provide the necessary pumping speed. Surface pumping, utilizing most of all of the available interior area of the vacuum enclosures, is required, due to the high gas loads anticipated. These loads result in large part from the nearly universal use of neutral beams for heating and/or refueling the devices. Large scale cryopumping, first utilized in the space program, is now being applied, using liquid helium cooling, in the high mass flow, moderate-to-high vacuum regime required for fusion research and for future fusion reactors.

Earlier Applications

The increased use of cryopumping in today's machines is largely a matter of scale. The ALICE (later Baseball) machine at Lawrence Livermore Laboratory made use of cryocondensation for beam line pumping about ten years ago, and later for removal of residual gases.

Figure 1 is a cross-section of one early beam line cryopump. The helium-cooled surface is shielded by a liquid nitrogen-cooled surface only on the outside, with the shielding extending axially beyond either end. The view factor to ambient temperature surfaces was such that no helium or neon shielding was needed. This pump - as intended is pump H_2 at 10^{-8} torrs; therefore the helium reservoir was placed under vacuum to achieve a helium

fig

bath temperature $\approx 2^{\circ}\text{K}$.

The pump had a measured speed of $100,000 \text{ litre} \cdot \text{s}^{-1}$ pumping H_2 at $\sim 10^{-9}$ torr. Circulation of liquid helium was by natural convection. The boil-off rate was $0.7 \text{ litre} \cdot \text{hr}^{-1}$, corresponding to a heat load of 0.5 watts. Except that this pump did not have nor require nitrogen-cooled baffling between the condensing surface and the pumped volume, it was similar in concept, if smaller in scale to the cryo-condensing pumps used in the High Voltage Test Stand (HVT5) at Lawrence Livermore Laboratory, on the Princeton Large Torus (PLT) beamlines, built by Oak Ridge National Laboratory for the Princeton Plasma Physics Laboratory, and the Tokamak Fusion Test Reactor (TFTR) beamlines, a prototype of which is being built for PPPL by LLL and the Lawrence Berkeley Laboratory.

Later, in the Baseball II machine (successor to ALICE), cryosorption pumping was used to reduce the helium partial pressure in the test chamber, resulting from minor leakage of the Baseball coil coolant. Here a drum, cross-grooved on the outside and coated with zeolite was cooled to $\sim 2^{\circ}\text{K}$, using the same low-pressure helium system which fed the beamline pumps.²

Baffled Cryopumps for HVT5

The High Voltage Test Stand, now in the process of being checked out at LLL is a flexible facility designed for testing various means of producing neutral beams at energies up to 200 KeV and tens of amperes of equivalent neutral current. Analysis³ of the vacuum pumping requirements of various arrays led to the provision of $\sim 950,000 \text{ litre-second}^{-1}$ of O_2 pumping speed for this facility in the form of one $500,000 \text{ l} \cdot \text{s}^{-1}$ main cryopump, (invariably located just downstream of the ion source) and three $150,000 \text{ l} \cdot \text{s}^{-1}$ modular cryopumps (to be spotted as required for various configurations). In these pumps, view factors between 4.2°K surfaces and 300°K surfaces are such as to require baffling between the condensing surfaces and the

pumped volume.

The basic array of cryogenic surfaces (used in both NITS pumps and in the TFIR beam lines) is shown in Figure 2. The pumping speed per unit area of such an array is given by,

$$\frac{S}{A} = \frac{\bar{v}}{4} (t^{-1} + c_{eff}^{-1} - 1)^{-1}$$

where

$\bar{v}$ = average molecular speed in the pumped volume

t = baffle transmissivity

c_{eff} = effective sticking probability.

The effective sticking probability is:

$$c_{eff} = c \left[1 - \sqrt{\frac{T_2}{T_s}} \frac{p_{vap}}{P_2} \right],$$

where

c = sticking coefficient

T_2 = gas temperature between baffle and condensing panel
($\sim 77K$)

P_{vap} = vapor pressure of condensate at T_s

T_s = temperature of condensate surface

For pumping of O_2 , the vapor pressure at 4.2 K is so low that $c_{eff} \approx c$ in the pressure range of interest (10^{-4} - 10^{-6} torr). For H_2 , on the other hand, the vapor pressure at 4.2 K is $\sim 5 \times 10^{-7}$ torr. Thus, at $P_2 \approx 2 \times 10^{-6}$ torr, a pump with a 4.2 K condensing surface will cease to pump H_2 . If the gas in the pumped volume is at $\sim 300K$, the pump base pressure will be $\sim 4 \times 10^{-6}$ torr. So, if hydrogen is to be pumped through the 10^{-6} torr range, the condensing surface temperature must be decreased, lowering the temperature to $\sim 3.2 K$.

decreases P_{gas} for H_2 by about an order of magnitude, which is sufficient for the pressure range required.

For pressures above these lower limits, $c_{eff} \approx c$, and the transmissivity of the optically opaque baffle array in figure 2 is ≈ 0.3 , so, for H_2 at 300K,

$$\frac{S}{A} \approx (2.33 \times \frac{1}{c})^{-1} \approx 31.2 \text{ litre} \cdot \text{second}^{-1} \cdot \text{cm}^{-2},$$

and for c near unity, $\frac{S}{A}$ is not sensitive to c .

A partially assembled cryomodule is shown in Figure 3. Pumping speed tests⁴ performed on this module gave $\frac{S}{A} \approx 9$ for D_2 and ≈ 13 for H_2 , indicating that c is in fact nearly unity and the speed is limited by the baffle transmissivity. Similar results have recently been reported by Hama, Ise and Benninger⁵ at Brookhaven National Laboratory.

The main cryopump is a scaled-up version of the cryomodules; but has, in addition, provision for storage of LiH_2 and LiH to permit it to be electrically floated at high voltage in certain HITS configurations. Figure 4 is a cutaway view of the main pump, and Figure 5 shows the cryogenic surfaces in assembly. This pump is now undergoing testing in place in the HITS. In both pumps the flooded panels (both LiH and LiH_2 coated) are of quilted stainless steel construction, electropolished for low thermal emissivity. The chevrons, which are cooled to ~ 20 K by conduction along their length, are of copper, blackened to minimize transmission of radiation from 300K surfaces.

TFTR Beamline Cryopumping

A cutaway view of the prototype beam line for the Tokamak Fusion Test Reactor is shown in Figure 6. The cryopanel construction is similar to that in the HITS pumps, except that a flat, rather than round, geometry is employed to fit the vacuum envelope geometry. The pumping array is composed of eight modular panels, suspended from the vacuum chamber lid,

four on each side of the vessel. The total pumping speed is approximately 2.5×10^6 litre $\cdot$ second $^{-1}$.

In order to make the pressure in the beamline downstream of the bending magnet as low as possible to minimize loss of neutral by ionizing collisions in the region where the stray magnetic field of the tokamak would deflect the ions out of the beam, a three-stage differential pumping scheme is used. The vacuum chamber is divided into three sections by sheet metal baffles with apertures just large enough to permit passage of the beam. With this arrangement, the third stage pressure is calculated to be 3×10^{-6} torr in the face of a 91 torr $\cdot$ litre $\cdot$ second $^{-1}$ gas load from the three ion sources in the first stage and a 13 torr $\cdot$ litre $\cdot$ second $^{-1}$ gas load from deflected ions impinging on the ion dump in the second stage.

The MIT Cryopumping System

The Mirror Fusion Test Facility to be built at MIT is an open-ended, minimum-2 mirror machine which will have 48 neutral beam injectors mounted in four arrays firing into the main tank. The geometry of the particle balance dynamics peculiar to mirror machines with their typically high fuel throughput, make it necessary to analyze the vacuum pumping system of the entire machine as an entity. Such an analysis⁶ shows that $\sim 3 \times 10^7$ litre $\cdot$ second $^{-1}$ of pumping speed will be required to obtain pressures in the 10^{-6} torr range in the plasma chamber.

The required pumping speed will be provided by cryopanelis lining most of the interior surfaces of the machines as indicated in Figures 7 and 8. In this machine it may not be necessary to use completely baffled pumps where view factors to warm surfaces are favorably low. Therefore, consideration is being given to the use of the geometry described by Sauter⁷, in which the life - cooled surfaces are infolded radially by life - cooled surfaces which are not absolutely opaque, but which

allow line-of-sight access only from the direction of other cold surfaces.

Operational Considerations

Perhaps the most important operating parameter of these large cryocondensing pump systems is the total heat load to the LHe-cooled surfaces. The total load is made up of components which may be steady, very slowly with time (quasi-steady), or be intermittent.

Examples of steady loads are radiation from Li_2 cooled panels and chevrons, heat conduction through supports, and heat conduction by residual gas at the system's base pressure. The latter is entirely negligible for pumping D_2 but may be significant if H_2 is pumped unless the panels are cooled below 4.2K.

One quasi-steady load is the decay of any radioactive isotope, such as tritium, which may be pumped, since, for a long-lived isotope, the decay heat increases with the amount condensed. In TFTR, this heat load will be insignificant; such may not be the case for future reactors, particularly if the plasma chamber proper is cryopumped as in the (non-tritium using) MFTF.

In pulsed system, intermittent loads include the enthalpy lost by the pumped gas in changing state from gas at $\sim 20\text{K}$ to solid at $\sim 4\text{K}$, neutron and gamma volumetric heating of the panel material, and eddy current volumetric heating owing to time-varying stray magnetic fields. In TFTR, the neutron, gamma, and eddy current heating are insignificant. In INRS and TFTR, both operating at pressures of 10^{-4} to 10^{-5} torr, the heat load due to the enthalpy change of the pumped gas is of the same order of magnitude as the radiant heat loads during the pulses; in TFTR with a 1:600 duty cycle, the averaged load is small.

Heat loads must, of course, be calculated for each situation; they generally come out to be ~ 1 watt per sq.cm. refer of pumping area.

Cryopumps, since they do not remove gas from a system, but merely immobilize it, must be defrosted periodically, whenever the concentration of hydrogen is high enough that an explosive mixture could form in an out-to-air vacuum accident. It is estimated² that from 12 to 50 torr - litres of hydrogen per litre of vacuum space is a safe limit on the amount that may be condensed.

The simplest way to defrost, especially with flooded, vertically oriented panels, is simply to depress the liquid helium level. A crude analysis⁸ of the system's pressure behavior has been made, and is described qualitatively, as follows.

The pressure first rises very rapidly, with a time constant given by the ratio of the volume to the pumping speed, to a value determined by the rate at which the level is being depressed. The pressure is then quasi-steady, but slowly rising, as the condensate evaporated for a given fall in liquid level is increasing, while the remaining cold pumping area is decreasing. During this time, the condensate is becoming concentrated more and more on the bottom part of the panel. Toward the end, the pressure rise becomes faster until a pressure is reached (typically $\sim 10^{-3}$ torr) at which the gas thermal conductivity is characterized by viscous behavior, the condensate is suddenly evaporated by the resulting high thermal flux, and the chamber comes up to a pressure determined by the amount of gas which had been accumulated.

Since the thermal conductivity of the gas is now relatively high, it is desirable to re-evacuate the volume quickly, using conventional roughing and high vacuum pumps, to minimize the subsequent temperature rise of the LHe - cooled panels.

The above procedure, while simple, has the disadvantage of needless warming of the panels during re-evacuation. The fact that the condensate

concentrates at the bottom of the panels prior to the sudden blow-off suggests that a method could be developed which would better conserve refrigeration. That is, if one small cryopump area could be served with its own life supply and could be arranged so as to have high gas flow conductance between it and the larger area, and could be valved-off from the rest of the system, then the larger area could be re-cooled without having been subjected to gas conductance heating, while only the smaller area, perhaps 5% of the total, would undergo rapid warming owing to sudden evaporation of the condensate⁸.

Fusion Reactor Cryopumping

In TFTR and MFTF, we are only beginning to face the pumping problems which will need to be solved for fusion reactors. Neutron and gamma heat loads may require shielding of cryocondensing panels. The engineering development of methods of cryotrapping and selective cryoabsorption should be pursued in order to handle the pumping of the helium fusion product.

The defrosting of cryopanel is a periodic nuisance in today's research devices; it would be an intolerable interruption of service in a fusion reactor. Several schemes for accomplishing the necessary defrosting without increasing the gas pressure in the pumped space have been proposed; one of these⁹ is illustrated in Figure 9. The moveable vacuum shield door shuttles up and down, covering one segment of cryopanel at a time. The covered segment is warmed, the gas pumped off via the ducts, and the panel re-chilled before the door is moved to the next segment. A good deal of engineering development will be required to make this or any other in-place defrosting scheme workable.

Conclusion

The vacuum pumping requirements imposed mainly by the use of neutral beam heating in present day fusion research devices are being met with large-scale cryopumping. These techniques will have to be brought to a much more highly sophisticated level through engineering development in order to solve the foreseeable problems associated with future fusion reactors.

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Fig. 1 - Early Beamline Cryopumping Used on ALICE.

Fig. 2 - Typical Baffled Cryocondensing Pump Array.

Fig. 3 - Partially Assembled HVIS Cryomodule.

Fig. 4 - HVTS Main Cryopump.

Fig. 5 - Cryosurfaces of HVTS Main Cryopump.
(LN₂-cooled surfaces in foreground,
LHe-cooled liner in rear)

Fig. 6 - Cutaway View of the Cryogenically-Pumped TFTR Beamline.

Fig. 7 JFTF Beamline Showing Probable Cryopump Arrangement.

Fig. 8 - MFTF Main Tank Showing Probable Cryopump Arrangement.

Fig. 9 - A Conceptual Design for In-Place Defrosting of Cryopanel.