DIRECT CRYOSORPTION PUMPING OF AN ENERGETIC HYDROGEN ION BEAM*

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Summary

Cryosorption pumps (CSP) are a prime candidate for the pumping of helium and deuterium-tritium (D-T) in tokamak divertor systems and may also see service in neutral beam injectors. However, the ability of a CSP to take high energy ions escaping from a plasma or neutral beam has not previously been demonstrated. In this study we arranged a 10-cm ion source of the type used in the Oak Ridge Tokamak (ORMAK) to inject a beam of ions directly into the inlet of a CSP. The pump contained two chevron baffles at 100K and 15K as well as a 15K cryosorption surface covered with a type 5A molecular sieve. The cryosurfaces were cooled by a closed-cycle helium refrigerator. For hydrogen ion pulses up to 11.5-keV energy and 1.3-A current, the pressure maintained during the pulse was only a few percent higher than that maintained with an equal flow of cold neutral gas. Pulse lengths of 100-300 ms were used. Calorimetric measurements showed that 40-60% of the I-V power was incident on the pump inlet. Cool-down and regeneration behavior of the pump will also be discussed.

Introduction

Cryopumping techniques hold considerable attraction in fusion vacuum applications because they offer the possibility of obtaining very high hydrogen isotope pumping speeds with relatively compact units and, in addition, introduce no contamination into the pumped chamber. Cryocondensation pumps operating at 4.2K with liquid helium have been used successfully to handle large hydrogen loads from neutral beam injectors on the Princeton Large Torus (PLT),[1] and their use is also planned for a number of much larger systems.[2] However, a disadvantage of cryocondensation is that the pumping panel temperature must be maintained very close to 4.2K in order to maintain acceptable pressure levels. This may prove difficult in large fusion reactor systems, which are subject to a variety of heat loads from such sources as neutron and thermal radiation from the plasma and surrounding chamber, eddy currents induced by rapidly changing currents in the confinement coils, and energetic particles escaping from neutral beam injectors or from the plasma itself. It has been proposed that cryosorption techniques might be superior to cryocondensation in such an unfavorable thermal environment[3] because the large internal surface area of sorption materials gives usable pumping action at temperatures well above 5K. Furthermore, with molecular sieve sorbents operating at 4.2K, it is possible to pump helium, the principal contaminant arising in a fusion reactor.

Pumping speed measurements for various molecular sieves with room-temperature hydrogen, deuterium, and helium gas have been reported by several investigators.[4] However, only a few studies have been carried out to date on the performance of either cryosorption or cryocondensation pumps with energetic particles. In this case, two processes can be considered: direct desorption of the condensed gas layer by incoming particle collisions, and heating of the cryopanel structure leading to release of condensed or sorbed gas. The ability of a cryocondensation pump to hold a condensed layer of deuterium in a high energy neutron flux has recently been investigated by Chou and Halama.[5] Both thermal (eV) and fast (MeV) neutrons were introduced at fluxes as high as $\sim 5 \times 10^9$ s^{-1} cm^{-2}. No evidence of deuterium desorption was found. Graham and Ruby have reported on the effect of high energy neutron pulses from the TRIGA reactor on a deuterium-loaded cryocondensation pump.[6] Neutron fluxes and energy distributions comparable to those expected from the Tokamak Fusion Test Reactor (TFTR) could be produced for energies ranging from thermal to >8.15 MeV. Although considerable desorption was seen, this was felt to be due not to the neutrons, but to the additional high gamma flux from the reactor, which exceeds the expected TFTR gamma flux by a factor of 10^3. These measurements indicate that neutron desorption in fusion reactor cryopumping systems should not be a problem, provided that the cryopanel cooling system can handle the neutron heating of the panel structure. This is not surprising, considering the weak interaction of neutrons with matter. However, incoming energetic hydrogen isotope atoms will interact much more strongly with the similar gas molecules already condensed or sorbed on the cryopanel. We report here on investigations to assess the ability of a cryosorption pump operating at 15-20K to handle hydrogen ions with energies up to 15 keV. The ions were produced by a 10-cm ion source aimed directly into the chevron baffle of the pump. It is found that pressure pulses with the ion beam on show only a very minor increase over pulses with gas only.

Apparatus

Figure 1 shows an overall schematic of the apparatus. The cryopump and ion source are connected to a rectangular observation chamber of 50-ℓ volume by 20-cm-diam couplings. A gate valve isolates the cryopump from the chamber. The chamber is provided with windows for observing the ion beam and contains a calorimeter for measuring beam power.

The ion source is a 10-cm duoPIGatron capable of operation at voltages up to 30 kV and currents up to 10 A. The characteristics and performance of this source have been described elsewhere.[7] It should be noted that the voltages and resulting beam currents used for this work are well below the source's optimum operating range. The accel and decel currents and voltages for the source are read out on storage oscilloscopes and are photographically recorded. Gas input to the source is controlled by a solenoid valve. The gas flow is measured with a Brooks Model 5810 0-200 SCCM mass flow meter with a digital readout. The slow response of this instrument allows accurate measurements only with continuous flow. Gas pressures are measured by a glass-enclosed Bayard-Alpert ion gauge located in the 20-cm pipe, a distance of 5 cm from the entrance to the cryopump. A Schulz-Phelps ion gauge is also installed in the observation chamber to allow measurements up to 1 torr. The beam power incident on the water-cooled calorimeter is calculated from the temperature rise shown by a ΔT-thermocouple sensor and the flow rate from a turbine flowmeter.

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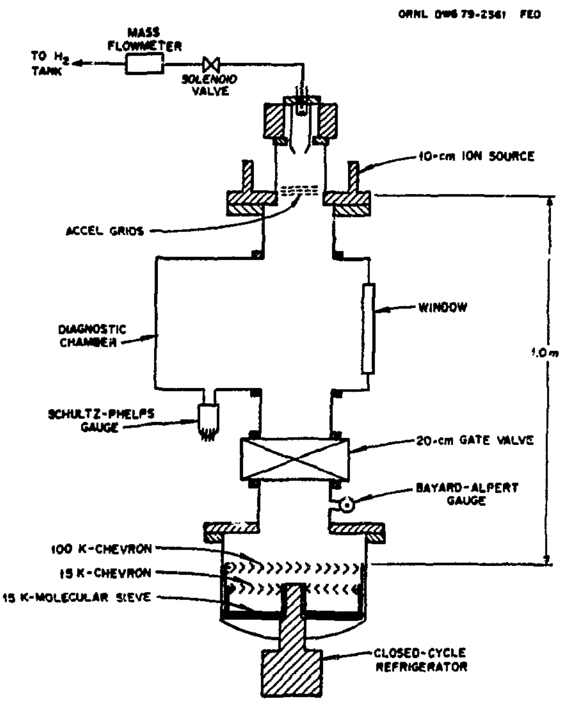

Figure 1. Overall schematic of apparatus.

Figure 2 shows a detailed cross section of the cryosorption pump. This pump was built by Excalibur Corporation for use in the Intense Neutron Source (INS) facility at Los Alamos Scientific Laboratory. An adapter plate matches the 40-cm inlet diameter of the pump to the rest of the system. The cryopanel is a 40-cm-diam circular aluminum plate, cross-milled with 1.6 x 1.6-mm grooves that are separated by 1.6 mm. A type 5A molecular sieve with a clay binder is applied to the cross-milled surface as an aqueous slurry and baked to hardness. To increase the sorption area, six rectangular (6 x 14-cm) sieve-coated plates are attached perpendicular to the main disc like vanes on a centrifugal pump impeller. The total available sorption area is 2100 cm^2. A cylindrical shield and chevron radiation baffle are welded to the sorption panel as shown to form a box that completely surrounds the molecular sieve surface. This is in turn surrounded by another radiation shield and chevron baffle that intercepts room-temperature radiation, water vapor, and other contaminants that freeze out at higher temperatures. The cryopanel and shield are bolted with soft lead shims to copper heat sinks on a stepped stainless steel tube that extends up into the pump case. The heat sink for the sorption panel has a threaded socket that accepts the second-stage cold station of an Air Products "Displex" Model CS-208 closed-cycle refrigerator. The refrigerator is screwed in until its first-stage cold station bottoms against the heat sink for the radiation shield. Indium shims are used between the refrigerator and heat sinks to improve heat transfer. The refrigerator can be removed and a heater screwed in to bake out moisture from the molecular sieve. Cooling tubes are attached to the radiation shield to allow quick cooldown with liquid nitrogen if desired. Gold-iron (Au-Fe) vs Chromel thermocouples with Scientific Instruments Model 3700 controllers are attached to the sorption panel and shield for temperature measurement. A type-K thermocouple is also attached to the sorption panel to monitor bakeout temperatures in the neighborhood of 250° C. Two more Au-Fe thermocouples are mounted on the refrigerator cold stations so that the temperature difference across the mechanical joints between the refrigerator and panels can be measured. Under no-load conditions, the refrigerator maintains the sorption panel at about 15K and the radiation shield at about 100K.

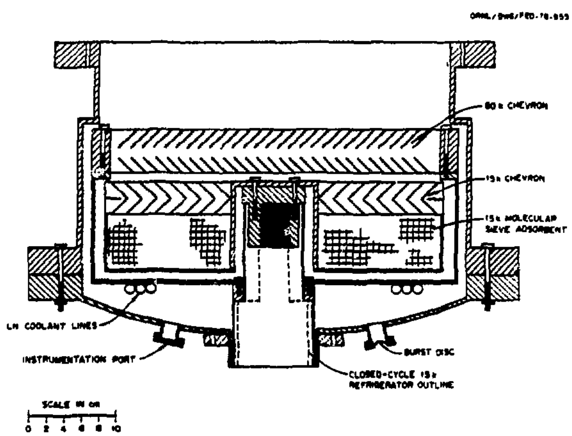

Figure 2. Cross section of INS cryosorption pump.

Procedure

Before the first cooldown, the pump was evacuated and the cryopanel baked at 250° C for 24 hours to remove moisture and contamination from the molecular sieve. The pump casing was not baked, but it became warm due to radiation from the hot interior. After turning off the heat, another 36 hours were required for the interior to cool to ambient temperature. After this the pump was always kept under vacuum and was baked again whenever it had remained at room temperature for periods longer than a few days. With the pump chamber in the 10^{-3} torr range, the refrigerator was started. Temperatures and pressures were monitored on a strip chart recorder. A typical cooldown is shown in Fig. 3, which indicates both pressures and temperatures as a function of time. Due to failure of the Au-Fe thermocouple on the cryopanel early in the experiments, temperatures were measured with the type-K thermocouple. Because of the low sensitivity of this thermocouple at cryogenic temperatures, the cooldown temperatures are only accurate to about $\pm$4K. The panel reached minimum temperature in about 12 hours. At this point the chamber pressure was in the mid-10^{-6} torr range. The ion source and observation chamber were roughed down, and the gate valve to the pump was opened. The source filaments were outgassed by slowly turning up the heater current. Ion beam pulses of varying energy and current were directed into the cryopump. The peak pressures during the pulse were read out on a storage oscilloscope and recorded photographically. For comparison, pulses were also generated with gas only. The amount of gas in each pulse was found by pulsing the gas valve of the source with the gate valve to the cryosorption pump closed and observing the pressure rise per pulse in the observation chamber. For a 100-ms pulse, from 1 to 2 torr-liters of hydrogen were injected per pulse; the exact amount varied with source conditions.

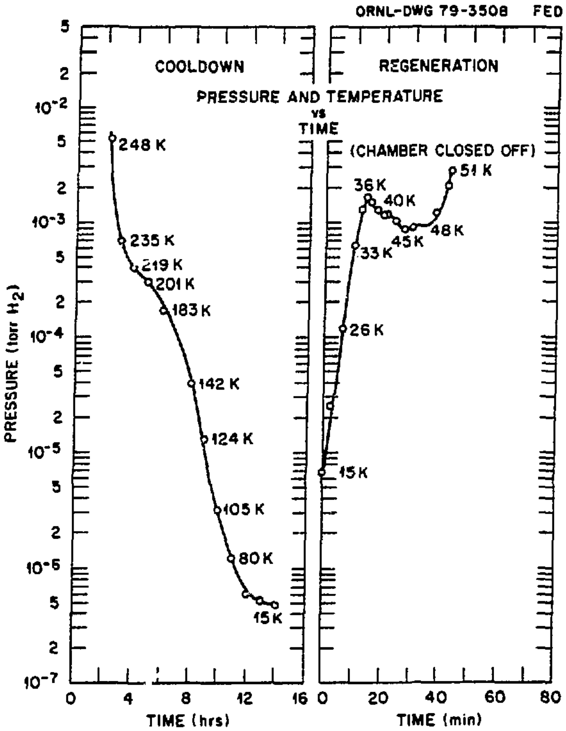

Figure 3. Cooldown and regeneration-pressure and temperature vs time.

The power of the ion beam can be estimated from the product of accel voltage and current, but a certain amount of power is lost by various processes such as interception by the grids, collisions with slow neutral molecules, and beam divergence inherent in the accelerator optics. Hence it is desirable to perform direct measurements with a target calorimeter. The water-cooled target was installed after the pressure measurements in the presence of the ion beam were completed. The target was fixed, and so it was not possible to measure beam power and then swing the target aside for measurements with the beam entering the cryopump. The power was found by integrating the response of the ΔT sensor and applying the formula

$$P = \frac{FC_H}{t_o} \int_{o}^{t_1} \Delta T \, dt,$$

where F and C_H are the flow rate and heat capacity of water, respectively, ΔT is the temperature rise, t_o is the beam pulse length, and t_1 is a time long enough for the ΔT sensor to return to equilibrium.

Several hundred beam pulses could be fired before the sieve became saturated with hydrogen and regeneration became necessary. Regeneration was accomplished by shutting off the refrigerator and allowing the cryopanel to warm to roughly 100K. The time required for regeneration was about 2 hours. The bulk of the sorbed gas was released between 70 and 80K. A pressure and temperature vs time plot for regeneration is shown in Fig. 3. Temperatures for this plot could be determined more exactly than for the cooldown, because the type-K thermocouple output at the lowest temperature of 15K was balanced out with a zero-suppressing circuit, allowing use of a much more sensitive voltage range on the strip chart recorder to measure deviations from the initial temperature. Error for the regeneration temperature is estimated at within ±1K. An interesting feature of the regeneration curve is the sudden fall in pressure at 36K followed by a pressure minimum at 45K. The cryopump chamber was valved off completely for the first portion of the regeneration. This indicates that the sieve actually reabsorbed hydrogen at 36K. At lower temperatures, gas is confined to pores near the sieve surface because the diffusion rate into the bulk of the sieve is low. At 36K, diffusion into the sieve bulk becomes fast enough to clear the surface sites and allow sorption of more gas from the chamber. However, as the temperature continues to rise, thermal desorption of the sieve soon dominates and the pressure again begins to rise. A similar phenomenon has been observed by Fisher.[8]

Results

General Comments on Pump Operation

Pulses were fired into the pump at the rate of one every 21 s. At the beginning of a pulse series, the panel temperature was between 12 and 15K, and rose to 19 or 20K as pulses were accumulated. The maximum pressure observed during the pulse would also rise to 50-80% during the first 8-10 pulses, presumably due to the reduction in sticking coefficient caused by the temperature rise and buildup of gas in the first few layers of pores in the sieve. If pulsing was stopped for 5 minutes and then resumed, the maximum pressure would again start out at the same lower value seen previously. This indicates that diffusion into the bulk of the sieve clears the surface on this time scale. With the pump freshly regenerated, the maximum pressure would remain quite constant during a pulse series. After several standard liters had been pumped, the peak pressure would begin to rise with successive pulses. At this point, the pump would be regenerated.

Operation of the closed-cycle refrigerator was quite reliable, and the pump could be maintained at low temperatures for weeks at a time with only a daily check of compressor inlet and outlet pressures. The freedom from storage and periodic transfer of liquid helium and nitrogen was a definite convenience. However, one disadvantage of a closed-cycle system became evident when a building power outage shut down the refrigerator and caused regeneration of the pump and loss of the system vacuum. Pumps with batch-fill cryogen dewars can survive this situation without difficulty.

Effect of Ion Beam

Typical pressure pulses associated with the ion beam are shown in Fig. 4. The beam energy range was 3-11.5 keV. The gas flow from the source was close to the maximum that the pump could handle, and peak pressures were in the 10^{-3} torr range. In Fig. 4, plots (b), (c), (e), and (f), the beam pulse begins 70 ms after the initial pressure rise. Plot (d) shows the source parameters for the pulse shown in (c). No evidence of any sudden gas desorption by the beam is seen along the leading edge of the pulses. For further comparison, gas was pulsed from the source with the arc and accel voltage power supplies off. Figures 4(a) and 4(b) illustrate such a comparison for a 50 ms pulse. The only visible effect of the 3.5 keV ion beam is a slight increase in the peak pressure, as shown in (b). Similar behavior is seen up to the highest beam energies used. With the energy

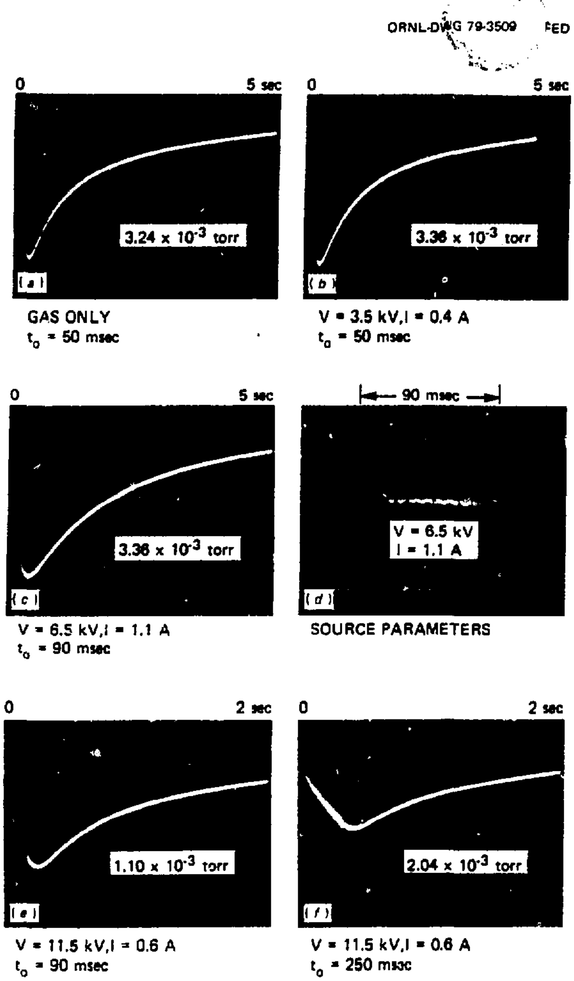

Figure 4. (a), (b), (c), (e), and (f): Pressure vs time for various ion source parameters. Labels give peak pressure during pulse. (d): Source parameters for plot (c). t_o = beam pulse length.

at 11.5 keV, the pulse length was increased in steps to 300 ms. No evidence of any pump instability or major release of sorbed hydrogen was seen. Up to 1075 pulses were injected before the pump was regenerated.

Beam Power

Table 1 shows values of beam power measured on the water-cooled target vs I-V power at various energies and currents. The measurements show that at least half the I-V power goes into the ion beam. It was originally expected that over 60% of the I-V power could be extracted in the beam. Evidently the accel voltages used were too far below the region for optimum operation of the source.

Table 1.
Beam power on target at various accel voltages and currents

V(keV)	I(A)	P_{IV}(kW)	P_{target}(kW)	Pulse Length (ms)	%
6.1	1.22	7.44	3.51	100	47
8.0	1.22	9.76	4.20	100	43
8.5	0.91	7.77	4.31	100	55
10.0	1.07	10.67	5.40	100	51
12.0	0.91	10.98	6.05	100	55

Discussion

Since the heat of sorption for a molecular sieve is less than 0.5 eV per sorbed particle, keV-energy particles entering the pump can desorb several particles each if they are not well accommodated to the chevron temperatures first. The fact that little or no evidence of desorption is seen indicates that the accommodation is sufficient in the two-chevron pump employed.

It should be noted that at the relatively low accel voltages and currents used, the source gas efficiency is poor, and the cold gas flow emerging from the source is much greater than the particle flow in the energetic beam. If a 1-A beam impinges on the 20-cm-diam area of the pump that is directly exposed to the source, the energetic particle loading at 50% transmission efficiency is 10^{16} particles cm^{-2} s^{-1}. It can be seen from Fig. 4 that the pressure at the inlet to the pump is about 10^{-3} torr during the time the beam is on. At this pressure, the flux of cold gas molecules into the pump is about 10^{18} cm^{-2} s^{-1}. Thus, the particle flux from the beam is of the order of 1% of the thermal gas particle flux. The beam flux is effectively an additional gas load on the pump inlet, and so the slight increase in peak pressure noted with the beam on is to be expected.

Because no evidence of catastrophic desorption or pump instability is seen even with the heavy cold gas load imposed by the source, it is reasonable to suppose that under more favorable cold gas loads, energetic particle fluxes greater than 10^{16} cm^{-2} s^{-1} could be tolerated. Much better pumping speed and total gas capacity could be achieved if the refrigeration system could maintain the cryosurface at 10-15K. Furthermore, the average energies of particles escaping from the edge of a tokamak plasma are expected to be much less than the 11.5 keV maximum energy used here. Hence, the results are encouraging for the use of large-scale cryosorption arrays for pumping of energetic particles in fusion systems.

Acknowledgment

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