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Summary

Plasma recovery systems in fusion reactors must be capable of exhausting a mixture of deuterium, tritium, and helium from the reactor between burns (and possibly during burns) to remove leaking or diverted plasma. Concentrations of helium in these mixtures may range from 1 to 15%. An Excalibur CVR 1106 cryosorption pump was tested to determine pumping speeds of 95% deuterium--5% helium. Tests were run with two different cooling configurations for the inner chevron (the chevron next to the cryosorption panel): (1) liquid helium boil-off vapor was routed through the chevron prior to venting (the normal mode), and (2) 77 K helium was backflushed through the chevron. Three distinct types of behavior were observed. At feed rates of $<1.2 \times 10^{-4}$ torr-liter sec^{-1} cm^{-2}, speeds decreased slightly with loading, regardless of the temperature of the inner chevron. Speeds as high as 3.7 liters sec^{-1} cm^{-2} were observed when the inner chevron was cooled by boil-off vapor; however, speeds were lower with the 77 K chevron ($\sim$2.2 liters sec^{-1} cm^{-2}). At high feed rates ($>1.2 \times 10^{-4}$ torr-liter sec^{-1} cm^{-2}), behavior was dependent on the temperature of the inner chevron. All runs began with a rapid decrease in pumping speed that resulted from the accumulation of helium in the test chamber after the frozen deuterium blocked the cryosorption surface. When the inner chevron was cooled by boil-off vapor, the pump recovered and the speed increased and remained steady near 1.9 liters sec^{-1} cm^{-2}. However, if the inner chevron was held at 77 K, operation had to be terminated because continuing system pressurization resulted in rapid cryogenic runaway. When the pump was cooled by liquid helium boil-off vapor, increased pressure affected the helium boil-off rate sufficiently to keep the inner chevron just cold enough to collect all (or a large fraction) of the deuterium, thus leaving the cryosorption panel clear to pump helium.

Introduction

The main vacuum systems in fusion reactors or burning experiments will need extremely high pump speeds for hydrogen isotopes and helium, essentially complete recovery of the hydrogen isotoeps, and complete containment of the tritium.[1] These requirements must be met within an acceptable cost range, without introducing impurities into the system, and probably in the presence of residual magnetic fields. Of all the available pumping methods, only cryosorption at temperatures near 4 K appeared likely to meet all of these needs. However, recent data on cryosorption pumping of each individual gas of interest (deuterium, hydrogen, and helium) suggested that new problems may arise in pumping mixtures of hydrogen isotopes and helium. At the pressures of interest($\sim10^{-4}$), hydrogen and probably deuterium appear to be pumped principally by cryocondensation rather than by cryosorption.[2] Condensation was indicated by the decline in hydrogen pumping speed at pressures near 10^{-5} torr, from a high initial speed (indicating cryosorption) to significantly lower speeds approaching those expected for cryocondensation. The vapor pressure of hydrogen at 4.2 K (corrected for thermal transpiration of 300 K is 1×10^{-5} torr. Thus the speed for condensation would be zero at 10^{-5} torr. Furthermore, this decline in speed occurred before a significant fraction of the molecular sieve capacity was collected on the pump panel and suggested that condensation of hydrogen was preventing sorption by the sieve. Further evidence that hydrogen was condensing on the surface of the sieve crystals, rather than sorbing uniformly in the sieve, was evident from the behavior of the pump after the hydrogen feed gas was turned off.[2]

The implications of these results to the pumping of mixed gases are obvious. If condensed hydrogen interferes with the sorption of hydrogen, one must consider the possibility that hydrogen (or hydrogen isotopes) may also interfere with the sorption of helium. However, helium, unlike hydrogen, cannot be pumped by condensation, and it did not appear likely that hydrogen isotopes would cryotrap the quantities of helium expected in a fusion reactor. This suggested that both hydrogen isotopes and helium could not be pumped by a single cryosorption (or cryocondensation) panel but would demand different panels, e.g., as a compound pump. To confirm the suspected behavior of single-panel pumps with mixed gases, a set of experiments were made using a 95% deuterium--5% helium mixture that is typical of the helium concentrations expected from recent tokamak designs.

Experimental

The experimental apparatus consisted of an Excalibur CVR 1106 cryosorption pump, a feed-gas system with adjustable feed rate, and a vacuum test chamber for the measurement of pumping speed. The pump and apparatus have been described in detail previously.[3] The pump contained a molecular sieve 5A (MS-5A) adsorption panel cooled by liquid helium. Boil-off gas from the liquid helium reservoir is normally routed through the inner chevron and radiation shield before discharge, as shown in Fig. 1(a). When the pump is operated at high pressures (in excess of 10^{-4} torr), the helium in the reservoir boils rapidly; hence the coolant flow to the inner chevron increases and lowers the chevron temperature. If the temperature of the chevron becomes low enough so that the equilibrium vapor pressure of any component is below its partial pressure, then it will accumulate on the chevron rather than the cryosorption panel. For example, if the partial pressure of deuterium is 10^{-4} torr, accumulation on the chevron will begin when the chevron temperature falls below 6.6 K. The pump can be forced to act much like a single cryosorption pump by controlling coolant flow through the chevron. This was accomplished by routing 77 K helium gas opposite to the normal direction of flow through the inner radiation shield and chevron (see Fig. 1(b)). This precludes any separation of components on different pump surfaces. To pump mixtures in this configuration, the helium must either be adsorbed through the frozen deuterium or trapped by the frozen deuterium.

A mixture of 95% deuterium and 5% helium was prepared by alternate additions of the two constituents to the 6-liter feed-gas reservoir. The reservoir was allowed to equilibrate for a day before runs were made.

Fig. 1. Schematic representation of Excalibur CVR 1106 cryosorption pump operating at high pressures for deuterium-helium mixtures: (a) normal operating mode with helium boil-off gas cooling inner chevron, and (b) modified operating mode with the inner chevron cooled by 77 K helium.

Gas samples taken before the first run and after the last run were found to contain 4.7 and 4.8% He respectively. All speeds reported here were calculated as the total feed rate divided by the total inlet pressure, assuming the gas in the chamber has the same composition as the feed. Specific speeds are based on the total surface area of the cryosorption panel (320 cm^2).

Results

Typical experimental results for runs at high feed rates are summarized in Fig. 2. The dashed curve shows data from a run made with both chevrons at 77 K. The feed rate was set at a value which would correspond to a pressure of $\sim 10^{-4}$ torr in the test chamber if the pump speed were the same as that observed for pure deuterium. The pumping speed fell quickly to zero. An explanation for this behavior is that deuterium condensed on the sieve panel and prevented helium sorption. Helium then accumulated in the test chamber, and the pressure increased. Additional heat transfer through the gas in the chamber caused intense boiling of the liquid helium in the reservoir. Cryogenic cooling was lost after only a few seconds of operation despite the fact that the liquid helium reservoir was filled just prior to the run. This is believed to be clear evidence that the deuterium (and tritium) cannot be pumped on an MS-5A panel at 4.2 K with helium at the concentrations and pressures needed in fusion reactor and in advanced fusion experiments. This shows that neither cryotrapping nor cryosorption will pump helium in the presence of hydrogen isotopes. Chou and Halama[4] have confirmed that deuterium will not cryotrap helium significantly at 4.2 K. They estimate that the ratio of condensed deuterium to trapped helium will not exceed $\sim 10^5$. At lower feed rates (corresponding to pressures below $\sim 5 \times 10^{-5}$ torr), the pump did handle the 5% helium mixture with both chevrons at 77 K. Apparently, the rate of diffusion of deuterium and helium with the MS-5A sieve is adequate for just slightly lower pressures. Although this is encouraging, the pump system must be stable and able to handle significantly higher pressures for short periods of time (e.g., immediately after the loss of plasma confinement).

As noted earlier, one solution to this problem would be to pump hydrogen isotopes and helium on separate panels; another possible solution may be to use a different sieve materials with a more open pore structure and higher diffusion rates. Although the commercial Excalibur pump was not designated for such operation, an attempt was made to operate the pump in a compound mode by using boil-off helium to cool the inner chevron to temperatures low enough to condensate deuterium. The results are shown by the solid curve in Fig. 2. At first the pumping speed declined as in the dashed curve, and the liquid helium in the reservoir began to boil intensely as before. Apparently, the boil-off rate from the reservoir was adequate to cool the inner chevron to a temperature low enough to condensate deuterium. The combination of condensation of deuterium on the chevron and sorption of helium (and some deuterium) on the sieve panel caused the pumping speed to quickly increase until steady pumping was achieved. During steady pumping, most of the deuterium was condensing on the inner chevron, allowing helium to be sorbed on the sieve panel. During this time, the test chamber pressure remained high enough to maintain the boiling of the liquid helium reservoir.

Fig. 2. Pumping speed as a function of helium accumulation for two runs at high feed rates.

Obviously, the Excalibur pump was not designed to operate under these conditions, and the performance was not as good as one could expect from data on pure gases. The pumping speed was less than that observed with deuterium. The pumping speed for helium is likely to be significantly lower than that for deuterium; so we suspect that the helium concentration in the test chamber was significantly higher than the 5% in the feed gas. However, these results do show that a compound pump can work, and improved performance can be expected when pumps are designed specifically for this combined operation. We hope to be investigating such compound pumps in the near future. A major improvement in performance over that of Fig. 2 should result by simply providing positive control of the temperature of both the hydrogen isotope and helium panels.

Figure 3 shows the steady-state pumping speeds observed for all runs with mixed gases. Details of each individual run are presented elsewhere.[5] Three distinct types of behavior were observed depending on the temperature of the inner chevron and the feed rate (or operating pressure). When the inner chevron was cooled by the helium boil-off gas and the feed rates were below $\sim 1.2 \times 10^{-4}$ torr-liter sec^{-1} cm^{-2}, pump speeds decreased monitonically during each run. Speeds as high as 1200 liters sec^{-1} (3.7 liters sec^{-1} cm^{-2}) were observed at the lowest feed rates. This speed is actually slightly higher than that observed previously with pure deuterium. Although this difference is probably within the scatter of the data, higher heat loads in these mixed-gas studies may have resulted in more condensation (i.e., more pumping) on the inner chevron.

Fig. 3. Average pumping speeds for 95% deuterium-5% helium as a function of pressure for an Excalibur CVR 1106 pump.

About 10^{-5} torr, the pump speeds dropped with increasing feed rates and leveled off at $\sim$700 liters sec^{-1}. Run 6, indicated in Fig. 3, is the same run shown as the solid line in Fig. 2, where the pump speed was plotted as a function of time. As noted earlier, both the helium boil-off rate and heat load on the inner chevron varied with the feed rate. No attempt was made to determine what role variations in the inner chevron temperature played in this behavior.

With the inner chevron temperature fixed at 77 K and at feed rates below $\sim 1.2 \times 10^{-4}$ torr-liter sec^{-1} cm^{-2}, the pump speed was essentially constant at 700 liters sec^{-1}. This stable behavior, however, was observed only at pressures up to $\sim 5 \times 10^{-5}$ torr. The cryogenic "run away" reported in Fig. 2 represents an attempt to operate beyond this point.

Design of a Compound Pump

In considering potential design features of a compound pump for helium and hydrogen isotopes, several options are possible, but some features of the design appear to be fixed. For instance, the hydrogen isotopes must be pumped by a panel "in front" of the helium panel. A chevron-shaped panel is an obvious choice for the hydrogen pump, but perhaps other shapes will be considered. This chevron can either be a cryocondensation pump operating near 4 K or a cryosorption pump operating at a higher temperature. In any case, however, the need for effective screening of hydrogen from the helium panel will require that the product of the sticking coefficient and the number of collisions with the panel (related to the flow resistance through the hydrogen panel) be near unity.

Although the fraction burn in most tokamak designs is relatively low ($\sim$1 to $\sim$15%), a small helium pump is not acceptable. If helium pumping are much smaller than hydrogen pumping speeds, the helium will accumulate in the plasma, reaching levels higher than the fraction burned. This is likely to cause premature termination of a plasma burn. Thus, the helium pumping panel must be as large or larger than the hydrogen pumping panel. Location of the helium pumping panel "behind" the hydrogen panel then means that the pumping speed for helium will always be less than that for hydrogen. However, the pumping speed for helium must not be allowed to get far below that for hydrogen. Construction of the hydrogen panel to provide maximum helium conductance to the cryosorption panel while providing adequate screening of hydrogen is an interesting design and experimental problem.

Several options are possible for the design of the (usually) liquid nitrogen-cooled thermal radiation shield and gas cooled chevron "in front" of the hydrogen panel. (This is similar to the way the Excalibur pump was operated for these experiments.) Another option, illustrated in Fig. 4, would incorporate the thermal radiation shield and gas cooler into the duct walls. This design would be particularly effective when neutron radiation shielding requires a relatively long duct with bends. The duct wall design would be complicated slightly, but it would provide significantly higher pumping speeds (a factor of 2 or more). Such gains are worth considering.

Fig. 4. Schematic representation of a high-speed compound pump incorporated into an exhaust duct of a fusion reactor.

Conclusions

Results presented here have direct bearing on the design of fusion reactor plasma recovery systems. Relatively stable pumping speeds can be achieved (for pumps sililar to the Excalibar pump) if the pump is operated to the left of the helium transition line shown in Fig. 3. This condition would limit operation to pressures below $\sim 5 \times 10^{-5}$ torr. Improvements in the choice of adsorbent (and possibly the panel operating temperature) are expected to move the transition line to the right and permit stable operation at higher pressures. However, if no improvement can be made, then the compound pump configuration becomes the logical choice for these systems.

Acknowledgements

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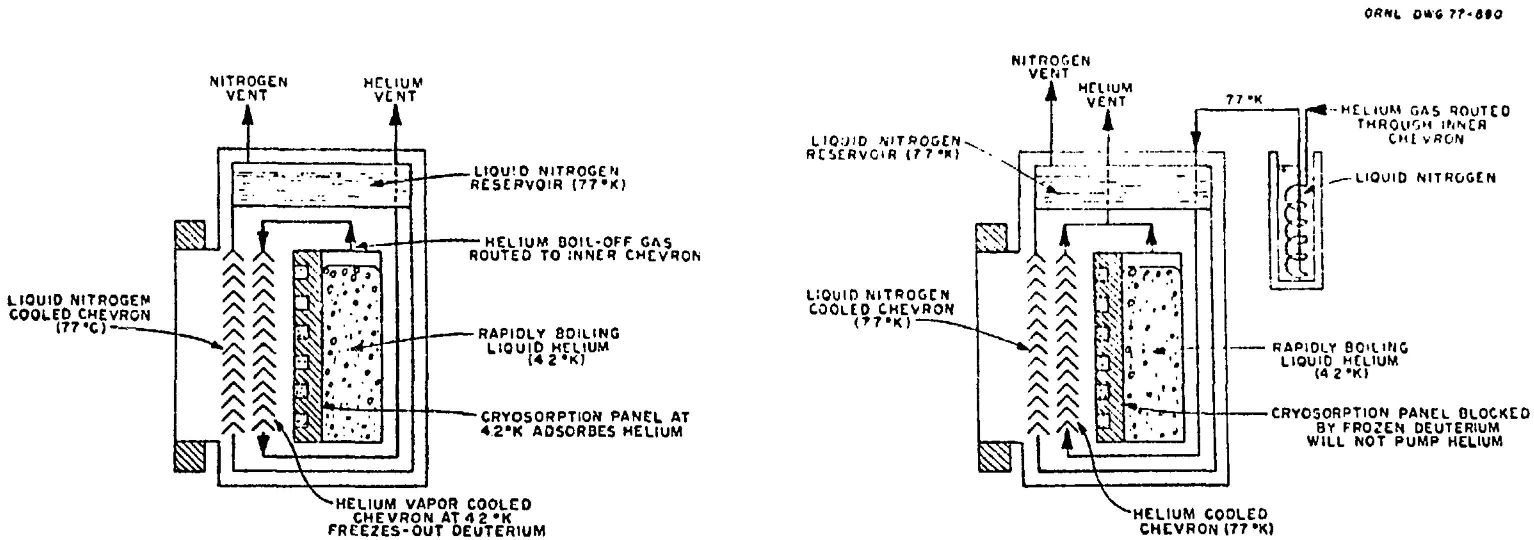

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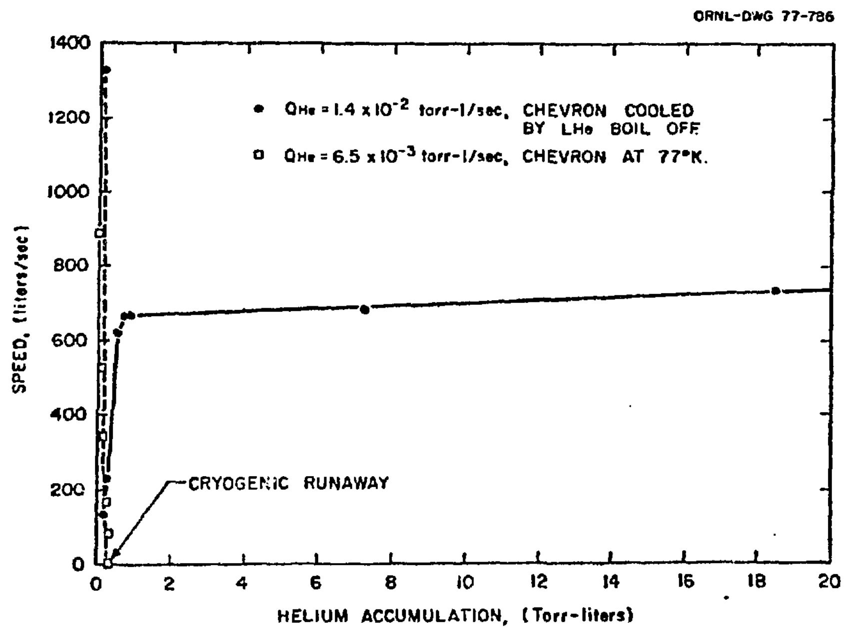

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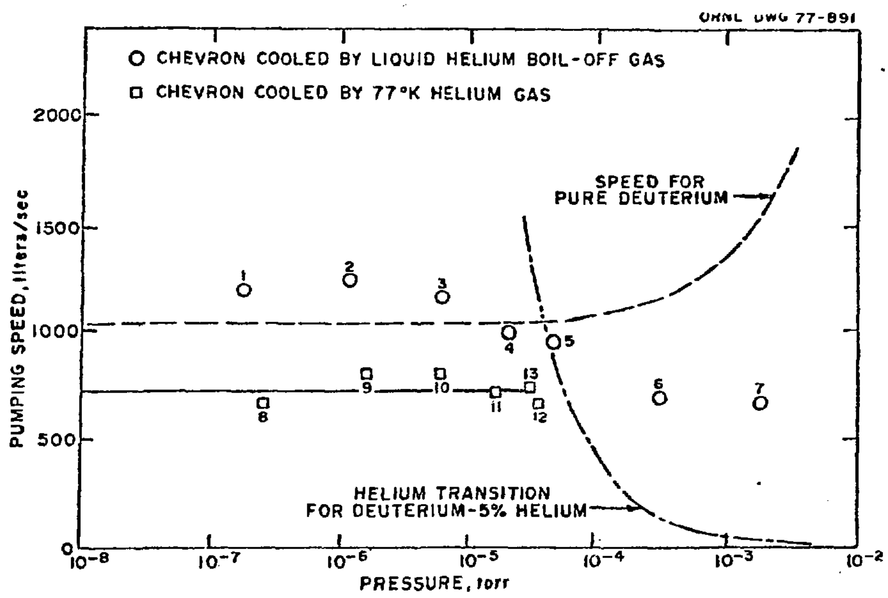
Fig. 2. Pumping speed as a function of helium accumulation for two runs at high feed rates.



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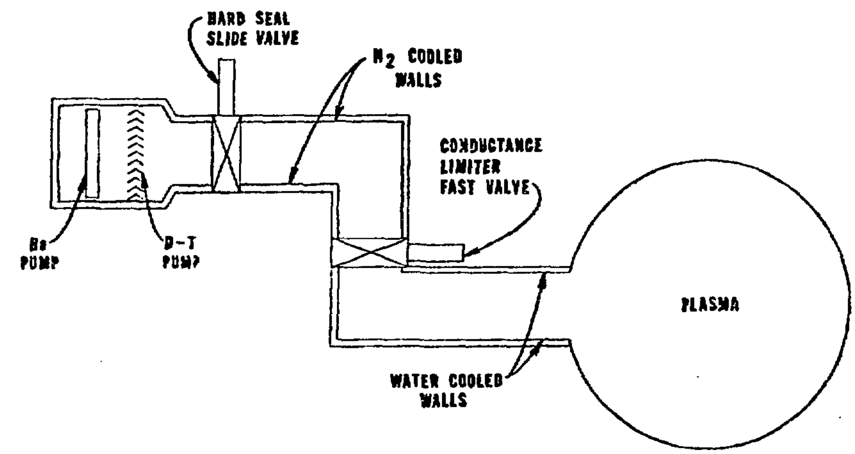

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