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A CONTINUOUS CRYOPUMP FOR STEADY-STATE MIRROR FUSION REACTORS

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ABSTRACT

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The characteristics of Mirror Fusion Reactors, i.e., steady state operation, a low neutral gas density and a large gas throughput require unique vacuum pumping capabilities. One approach that appears to meet these requirements is a liquid helium cooled cryopump system in which a fixed portion can be isolated and degassed while the remainder continues to pump. The time to degas a rotating, fixed portion of the pumping area and the ratio of that area to the total area fixes the gas inventory in the chamber. It follows that the active pump area maintains the required neutral gas density and the time averaged degassing rate equals the gas throughput. We have built such a cryopump whereby the gas condensed (deuterium) on the liquid helium cooled panel can be transferred to a collector pump and subsequently to an exterior mechanical pump and exhausted. At panel loadings as high as .55 torr-litres/cm² the gas leakage during degassing is less than 8% and the degassing time is less than 10 minutes. Scaling to reactor size appears to be feasible.

INTRODUCTION

The next generation of Magnetic Mirror Fusion Experiments such as TDF (Technology Development Facility) and MFTF-B+T (Mirror Fusion

Test Facility-B, Tritium Upgrade) will have reactor grade plasmas burning tritium in a steady state mode (more than 10 hours). Under such conditions, it is necessary that the vacuum pumping system also have steady state capability. Further, since Magnetic Mirror Fusion devices are driven by low ($\sim 30\%$) gas efficiency neutral beams, the gas loads are very high requiring internally deployed cryogenic pumping panels.

For steady state operation, the cryocondensing deuterium-tritium pumping panels are designed to be isolated and degassed in discrete, sequential groups while the remainder of the panels continue to pump unperturbed by the degassing process. The degassed effluent from the isolated cryopanel passes through a valve connecting the panel to a gas tight liquid nitrogen cooled shroud that encloses a small liquid helium cooled panel on which it is collected. The valve is then closed, the collector panel degassed, and the gas conducted to the external mechanical pump and on into the fuel clean-up system. A further consideration is the amount of deuterium-tritium allowed to accumulate in a regenerable cryopumping system. Although the allowable DT inventory has not been fixed for TDF or MFTF-B+T, the objective is to make the amount a practicable minimum.

For such a scheme to work, there must be an installed pumping capacity that is greater than that needed to maintain the required system pressure. The excess capacity must degas in a continuous, sequential manner at a rate equal to the through-put

of the reactor. Further, since the degassing flow rate must be equal to the gas input and only a fraction of the total pumping system is degassing at any one time, the degassing process must take place at a pressure several orders of magnitude higher than the required system pressure.

The quantity of gas accumulated on the cryopanel and the collector panels during steady state operation (the gas inventory in the vacuum vessel) is related to the gas through-put, the degassing cycle time, the excess capacity fraction and the gas leakage into the vessel during degassing. Assuming the degas leakage to be negligible (pressure rise less than a factor of two), the gas inventory can be derived in the following way:

$$Q = \text{Reactor gas through-put } \frac{\text{torr-liters}}{\text{sec}}$$

$$P_a = \text{Allowable reactor pressure (torr)}$$

$$S = Q/P_a \text{ Required pumping speed } \frac{\text{liters}}{\text{sec}}$$

$$S = sA$$

$$s = \text{Specific pumping speed } \frac{\text{liters}}{\text{sec-cm}^2}$$

$$A = \text{Cryopanel area required to yield } S \text{ (cm}^2\text{)}$$

$$\gamma A = \text{Total installed pumping area (cm}^2\text{)}$$

$$A(\gamma-1) = \text{Pump area available for degassing (cm}^2\text{)}$$

$$\frac{\gamma}{\gamma-1} = \text{Number of degassing units or pumping units}$$

$$t_c = \text{Total cycle time (pumping time + degassing time) of an } A(\gamma-1) \text{ pump-area unit (sec)}$$

$$t_d = \text{Degassing time of an } A(\gamma-1) \text{ pump-area unit (sec)}$$

Since the gas flow into the reactor must equal the gas flow out

$$Q = sAP_a = S_d P_d$$

where S_d (l/sec) is the degassing or collector pump speed and

P_d (torr) is the collector pump pressure during degassing.

Further, the amount of gas degassed during the time t_d equals

the amount pumped during the time $(t_c - t_d)$ for a given

$A(\gamma-1)$ pump-area unit and

$$S_d P_d = sA(\gamma-1)P_a(t_c - t_d) \quad \text{or}$$

$$\gamma = \frac{t_c}{t_c - t_d}$$

Summing up all the gas inventory in the panels at any given time as a function of γ gives

$$I_p = sAP_a(t_c - t_d) \frac{\gamma}{2} = \frac{Q}{2}t_c$$

Finally, the inventory in the collector pump for any $A(\gamma-1)$

degassing unit equals the gas collected on that unit during its pumping time:

$$I_c = \frac{Q(t_c - t_d)}{(\gamma/\gamma-1) - 1} = Qt_d$$

The total inventory, panels plus collector pump is

$$I_T = I_p + I_c = \frac{Q}{2}t_c + Qt_d = Qt_d \frac{3/2 \gamma - 1}{\gamma - 1}$$

Figure 1 shows a normalized plot of inventory I_T/Qt_d versus excess capacity $(\gamma-1)$. A reasonable choice for excess capacity appears to be between 10 - 20% or $\gamma = 1.1 - 1.2$.

REGENERABLE CRYOPUMP DESIGN

The TDF continuous cryopumping system is based on a regenerable design developed and tested at LLNL. It can be regenerated without reintroducing an unacceptable portion of the pumped gas back into the high vacuum space. A photograph of the prototype tested at LLNL is shown in Figure 2. The pump features a set of liquid helium cooled panels for condensing the deuterium. These panels are provided thermal shielding by a series of "Z" shaped double chevrons that when open allow passage of the deuterium to the condensing panels from two sides. For regeneration the condensing surfaces are isolated from the high vacuum space by closing the louvers. The liquid helium is then purged from the condensing panels releasing the condensed deuterium. The deuterium flows through an isolation valve between the closed panel and the liquid helium cooled collector pump which is periodically degassed to the exterior mechanical pumping system.

Figure 3 shows the panel subassembly. Both the liquid helium and liquid nitrogen portions of the panel were made of tube and sheet weldments of 6061-T6 aluminum. They were designed to mesh with each other with no contact and were clamped into an assembly with four fiberglass clamps. A cross-section of the panel is shown in Figure 4. The outer shield louvers are hinged to the inner fixed louver that carries the liquid nitrogen coolant. The moveable louvers are blackened to prevent the 300⁰K radiation from reaching the liquid helium cooled condensing surfaces. To transfer this thermal load to the liquid nitrogen, it was

necessary to put 10 layers of .003 in. aluminum foil around each hinge with good thermal contact on either side. Without the foil, the moveable louvers would equilibrate at 200°K ; with the foil, they approached the fixed louver indicated temperature of 90°K . Using multiple layers of thin foil in this manner did not impede the hinge motion, and as the rotation, full open to closed, is only 57° it did not significantly stress the foil. The linkage that operates the louvers is an overcenter toggle arrangement hand operated through a Wilson seal. When the louvers are closed, the panel and the upper and lower liquid nitrogen cooled shroud form a relatively gas tight volume for degassing the panel.

The collector pump shown in Figure 2 is connected to the lower shroud by a 3 in. dia. valve. The outer shell of the collector pump is cooled by thermally circulating liquid nitrogen and encloses a liquid helium vessel. The bottom of the helium vessel has (17) one inch tubes six inches long which provide 2000 cm^2 of condensing surface. A three in. stainless steel tube connects the outer shell to an external gate valve for degassing the collector pump. All the cryogen assemblies, LN_2 and LHe are 6061-T6 aluminum. Only the thermal isolators are stainless steel.

TESTING

A schematic of the test set-up is shown in Figure 5. The test panel has an active projected area (both sides) of 1 m^2 . The pumping speed for deuterium is 61,000 l/sec. for a capture

coefficient of 20%. The collector pump and appendage pump have speeds of 700 l/sec. and 5500 l/sec., respectively for D_2 .

The tests were designed to determine the degassing characteristics of the panel including:

- Degassing cycle time - t_d
- Louver leakage during degassing
- Degassing pressure (vs) gas load
- Gas transfer time from panel to collector pump

The system was fully instrumented with ion gages, capacitance manometers, liquid level indicators, flow meters and temperature sensors. Initial conditions for each test were:

- All reservoirs both liquid nitrogen and liquid helium full
- Appendage pump (valve #8) isolated
- External mechanical pump (valve #7) isolated
- Collector pump (valve #6) isolated
- Louvers to test panel open
- Gas bleed valve #2 closed
- System pressure $\sim 7 \times 10^{-9}$ torr

All panel loadings were made at the same deuterium gas flow rate,

i.e., $800 \frac{\text{atm-cm}^3}{\text{sec}}$ or 10.136 torr-liters/sec. The loadings were 1600, 3200 and 6400 atm-cm³ (1600 atm-cm³ is more than twice the loading per m² that would occur in TDF). After the panel

was loaded, the degas cycle was started. Sequentially, the following events occurred:

- Valve #8 to the appendage pump opened
- Valve #6 to the collector pump opened
- Louvers on test panel closed
- Liquid helium purged from the test panel
- Gas load transfers from test panel to collector pump
- Appendage pump valve #8 closed
- Collector pump valve #6 closed
- Louvers opened
- Test panel refilled with liquid helium
- Panel ready for reloading

The elapsed time for the degas cycle (all manual operation) averaged over about 100 cycles is 7 min. The actual gas transfer time is about 25 sec. as indicated by Figure 6 which is a simultaneous X-Y recording of the pressure signals from the capacitance monometers #3 and #4 in Figure 5. The lower curve is the pressure time history in the 1200 liter vessel during the gas transfer while the upper curve follows the pressure in the closed panel.

An attempt was made to estimate the closed louver leakage from the data in Figure 6. While the data was very repeatable, the pumping speeds of the collector and appendage pump change significantly with pressure during the viscous flow gas transfer. Further, there is no way of determining gas

temperature during the degas cycle. Thus, the louver leakage estimated from Figure 6 ranged from 8% to 30%, depending on reasonable assumptions for pumping speeds and gas temperature. To narrow this range, we filled the test panel and collector pump shielding with liquid nitrogen and evacuated the chamber with the appendage pump (no liquid helium in the test panel or collector pump). When the pressure reached high vacuum ($< 10^{-7}$ torr), the chamber was isolated from the appendage pump and a pressure vs. time curve was drawn on the X-Y recorder for a flow rate of $10^{\text{torr-liters/sec}}$ up to a pressure of 4.5 torr. The pressure signal was taken by the #3 (Figure 5) capacitance manometer on the 0-10 torr scale. Thus, from the slope of this curve generated under temperature conditions nearly identical to those during test panel degassing, we could measure the amount of gas captured on the collector pump during one or several degassing cycles such as shown on Figure 6. Four such measurements were made, and they all indicated a louver leakage rate of ~30%.

An acceptable leakage rate estimated from the TDF parameters is 5-10%. I believe 5% can be readily achieved using close fitting extrusions rather than weldments in the moveable louvers and optimizing the conductance to and the speed of the collector pumps. No attempt was made to optimize the test panel for leakage; the point was to determine reliability, repeatability, operation characteristics, and concept feasibility (all of which appear to be acceptable).

We are currently retrofitting the LLNL test panel for argon cryosorption of helium to determine the degassing characteristics of a D_2 , He pump. Further, LLNL is party to a joint proposal with Grumman Aerospace Corp. to build and test a two panel continuous pump.

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FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

TEST STAND SET-UP

- ① 1200 LITER VACUUM VESSEL
- ② DEUTERIUM GAS BLEED SYSTEM
- ③ "BARATRON" (0-1 TORR) VESSEL PRESSURE
- ④ "BARATRON" (0-1 TORR) PUMP SHROUD PRESSURE

- ⑤ PUMP SHROUD
- ⑥ COLLECTOR PUMP & VALVE ASSEMBLY
- ⑦ VALVE TO EXTERNAL MECHANICAL PUMP
- ⑧ 30 cm VALVE TO APPENDAGE PUMP
- ⑨ LIQUID HELIUM COOLED APPENDAGE PUMP

FIGURE 5

FIGURE 6