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THE PERFORMANCE OF BNL-TSTA COMPOUND CRYOPUMP *

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1. INTRODUCTION

In fusion reactors, various pumping systems, with extremely high pumping speed, will be required to evacuate the reactor chamber during and between burns. The plasma exhaust gases are expected to be largely mixtures of helium and hydrogen isotopes, therefore, these pumping systems must be capable of containing and separating, for the recovery, the hydrogen isotopes from helium and other impurities. A vacuum facility using cryopumping can fulfill these requirements. The advantage of cryopumping lies in its ability to achieve very high pumping speeds (proportional to the area of cryosurface) and very low equilibrium pressure while confining the pumped species onto cryosurface. The hydrogen isotopes can be pumped efficiently by either cryocondensation^{1,2} or cryosorption³⁻⁵ at liquid helium temperature. Helium, however, can only be pumped by cryosorption⁶ at low temperature. The two most commonly used adsorbents for cryosorption pumping of helium are activated charcoal and molecular sieves. The cryosorption pumping of helium by coconut charcoal has been studied in detail⁷ and found to have high pumping speed and large adsorption capacity. We have therefore designed a compound cryopump using cryocondensation pumping for hydrogen isotopes and cryosorption pumping with coconut charcoal as adsorbent for helium. This compound cryopump was subsequently built (by Janis Research, Stoneham, MA) and has been tested at Brookhaven, fulfilling the design requirements and are delivered to Tritium Systems Test Assembly (TSTA) Vacuum Facility at Los Alamos Scientific Laboratory (LASL) for on-line operations.

The basic construction of this compound cryopump and the results obtained during test runs at Brookhaven are reported below.

II. DESCRIPTION OF SYSTEMS

A. The TSTA Vacuum Facility

The TSTA Vacuum Facility⁸ at LASL is intended to demonstrate realistic fuel supply and cleanup operations similar to those anticipated on fusion devices. It has all the elements for the pumping system of a fusion reactor as shown schematically in Fig. 1. The heart of this vacuum facility is the compound cryopump. During the on-line operation, the appropriate gas mix is diverted from the TSTA main stream and injected into a torus simulator, from which it is pumped by the TSTA compound cryopump and then returned to the main loop during the regeneration cycle. The helium is not returned to the main stream during regeneration but is exhausted through Zr-Al getter, turbomolecular pump and rotary vane pump into a stack.

Compound cryopumps which are to be evaluated and accepted by TSTA Vacuum Facility must meet the following requirements:

- (i) provide high pumping speed
 - 10,000 - 16,000 ℓ /sec for deuterium and tritium
 - 1,500 - 3,200 ℓ /sec for helium.
- (ii) have large capacity
 - > 34,000 Torr $\cdot \ell$ for deuterium and tritium
 - > 3,400 Torr $\cdot \ell$ for helium.
- (iii) be able to pump a mixture of deuterium, tritium, helium (10%), and other impurities.

- (iv) be able to start pumping at an initial torus pressure 7.5×10^{-3} Torr with an initial flow rate of 52 Torr · l/sec and be able to achieve a blank off pressure of $\sim 1 \times 10^{-8}$ Torr.

- (v) be able to regenerate hydrogen isotopes and helium separately.

B. The BNL-TSTA Compound Cryopump

The designed features of the BNL-TSTA compound cryopump (called the cryopump hereafter) is to demonstrate the feasibility of using cryocondensation pumping for hydrogen isotopes and using cryosorption pumping with coconut charcoal as adsorbent for helium isotopes. Hydrogen isotopes are pumped by both cryocondensation and cryosorption, therefore, to avoid saturation of the cryosorption panel and to achieve separate regeneration, they should be pumped on the condensation panel first. The BNL compound cryopump has been designed to meet these features. Figure 2 and 3 show the overall drawing and picture of the cryopump. Except the chevron baffles and the charcoal panel, this cryopump is constructed entirely from 304 SS. To minimize the conduction heat load to the cryogen reservoirs, all the reservoirs are suspended by thin wall tubes which also serve as transfer and venting lines. The major components of the cryopump are described below:

- (1) Pump Body. The vertically mounted cryopump has 40 cm I.D. bottom inlet port with NW-400 ISO-Pneurop flange, 8 inch O.D. Conflat flange on the top as regeneration port and other Conflat flanges for connecting roughing pumps and monitoring instruments. Indium (with 2% silver) seals are used for the 35 inch O.D. double grooved flanges and the 21 inch O.D. flanges.

- (ii) LN₂ Reservoir. The liquid nitrogen (LN₂) reservoir, the thermal anchor and the chevron baffles serve as radiation shielding, remove the condensable and reduce the temperature of the incoming gases. The cross sectional view of the chevron baffle is shown at the right hand corner of Fig. 2. The baffles which are anodized to minimize radiation heat load to inner liquid helium (LHe) reservoirs have calculated transmission coefficients about 27% for molecules and less than 1% for photon when emissivity is ~ 0.9 .
- (iii) Cryocondensation Panel. The outer LHe reservoir and chevron baffles function as cryocondensation panels for hydrogen isotopes and radiation shielding for inner LHe reservoir. All the hydrogen isotopes are pumped at this stage.
- (iv) Cryosorption Panel. Helium gas is adsorbed on the LHe cooled charcoal panel. The charcoal panel consists of 32 triangularly-shaped ($\sim 40 \text{ cm}^2$ area each) metalized charcoal plates, made of coconut charcoal imbedded in Sn-Ag alloy, bolted to the bottom of the reservoir. Metalized bonding has several advantages over organic adhesive; better thermal conductivity, less temperature gradient, higher resistance to radiation damage and nonblocking of the porous path on the surface of charcoal granule. The charcoal panel as well as the bottom of the reservoirs are shown in Fig. 4.
- (v) Instrumentation. Two heaters, two temperature sensors and one LHe level probe are installed in each LHe reservoir. The heaters are for controlling the temperature of the panels

during regeneration. The temperature sensors are silicon diode type requiring $10\mu\text{A}$ constant current supply and are installed at center and edge of each panel. The voltage response of these sensors ($\Delta V/\Delta T$) is greater than 20 mV/degree when temperature is less than 20°K .

III. THE PERFORMANCE OF THE CRYOPUMP

To evaluate the performance of the cryopump, several test runs were done at Brookhaven during which the cryopump behaved as expected, however, due to the limitation of equipments at Brookhaven, the capability of this cryopump could not be fully demonstrated. The experimental setup, the test procedures and the obtained results are summarized below.

A. Experimental Setup

A setup shown schematically in Fig. 5 was attached to the cryopump to allow a controlled amount of gas or mixture of gases flow continuously into the system. This was accomplished by using the orifices C (with a known conductance 10 ℓ/sec for hydrogen and 7 ℓ/sec for helium) between gas inlet chambers and gas mixing chamber and by monitoring the pressures of the gas inlet chambers with Schulz-Pheleps type ionization gauges (operated between 10^{-6} Torr and 1 Torr). The pressure inside the gas inlet chambers were controlled by the Granville-Phillips servo-driven bleed valves. Varian quadrupole residual gas analyzer and Bayard Alpert type ionization gauge were installed at the cryopump side to measure the total and partial pressures of gas species. Turbomolecular pumps were attached to the cryopump and gas mixing chamber to evacuate the system initially and during regeneration.

B. Measurement

After the initial evacuation of the system to a pressure $\sim 1 \times 10^{-5}$ Torr by turbomolecular pumps, the reservoirs were filled with LN_2 or LHe . The temperatures of the cryosurface were near 4°K and the background pressure was $\sim 3 \times 10^{-9}$ Torr at this moment. The feeding of the desired amount of gas or gases was started by slowly opening up the servo-driven bleed valves and by monitoring pressures inside the gas inlet chambers. During the runs, the flow rates of helium and hydrogen were varied to observe the effect on pumping speeds, and the equilibrium pressures of the cryopump were measured by interrupting the gas flow.

The flow rate Q was calculated from $Q = C(P_1 - P_2)$ here C is the conductance of the orifices, P_1 the pressure in the gas inlet chambers and P_2 the pressure at cryopump. During these runs, P_1 were much greater than P_2 and P_m , the pressure in the gas mixing chamber, ($P_1 \gg P_m > P_2$), therefore $Q \approx CP_1$. The pumping speed S was calculated by $S = Q/P_2$. The surface coverage (the amount of gas pumped at that moment) was calculated by integrating of flow rate versus time. When pumping the mixture of hydrogen and helium, the individual partial pressure and flow rate were used in the calculation.

The cryogen consumption rate and the heat load of each reservoir with and without gas input were determined by the boil-off method. Dry gas flow meters (Singer-American DTM-200) were connected to the exhaust lines of the LN_2 and LHe reservoirs to measure the boil-off rate of the cryogens.

C. Results

- (i) The Cryosorption Pumping of Helium. The pumping speeds of helium were evaluated as a function of gas flow rate as well as surface coverage on charcoal panel and are shown in Fig. 6. At a flow rate of 0.7 Torr·ℓ/sec, the initial pumping speed was ~ 5,000 ℓ/sec, however, after ~ 200 Torr·ℓ of helium was adsorbed, the pumping speed dropped to less than 3,000 ℓ/sec. Beyond that, it levelled off and decreased slowly with increasing surface coverage. At the same surface coverage, the pumping speed of helium increased with decreasing flow rate. The total adsorption capacity of charcoal panel for helium is greater than 5,000 Torr·ℓ, beyond that the pumping speed dropped below 1,000 ℓ/sec and made it impractical to continue pumping. The decrease of pumping speed with increasing surface coverage and flow rate can be explained by the rate of migration of helium from the surface to the inner bulk of charcoal granule. When the rate of adsorption exceeds the rate of migration (which occurs at higher flow rate and surface coverage), the available area on the outer surface of charcoal granule diminishes which causes a decrease in pumping speed.
- (ii) The Cryopumping of Mixture of Helium and Hydrogen. A test run was performed by feeding a mixture of 80% hydrogen and 20% helium continuously into the system. The pumping speeds for helium as shown in Fig. 6 were lower than those when pumping pure helium. This decrease (~ 30%) in pumping speed might be caused by the large uncertainty in measuring the helium

partial pressure at the cryopump side. As expected the cryocondensation panel produced a far higher pumping speed for hydrogen than the cryosorption panel to which the helium flow was restricted by the chevron baffles. The initial pumping speed for hydrogen was $\sim 16,000 \text{ l/sec}$, as the thickness of the condensed hydrogen reached several monolayers, the vapor pressure of hydrogen increased to $\sim 4 \times 10^{-6} \text{ Torr}$ (measured by Bayard-Alpert gauge and residual gas analyzer) and made pumping speed measurements rather difficult. This vapor pressure corresponds to a temperature of $\sim 4.8^\circ \text{K}$ for the cryocondensation panel. At this temperature, the vapor pressure of the condensed deuterium and tritium film will be less than $1 \times 10^{-8} \text{ Torr}$.

- (iii) The Cryogen Consumption Rate and Heat Load. The cryogen boil-off rates (in l/hr) and the corresponding heat load (in watts) of each reservoir with and without gas input are summarized in Table I. The heat load of both LHe reservoirs increased linearly with increasing gas flow rate up to $\sim 5 \text{ Torr} \cdot \text{l/sec}$, beyond that the boil-off of LHe became excessive and prohibited accurate measurements. The heat content of hydrogen² from 80°K to 4°K is $\sim 0.2 \text{ watt/Torr} \cdot \text{l/sec}$, the heat of adsorption⁷ of helium on charcoal is $\sim 300 \text{ cal/mole}$ ($\sim 0.2 \text{ watt/Torr} \cdot \text{l/sec}$). The increase in heat load (i.e., $\sim 0.3 \text{ W}$ when pumping $1 \text{ Torr} \cdot \text{l/sec}$ of helium) to the inner LHe reservoir was consistent with the amount caused by

the heat of adsorption of helium, however, that of the outer LHe reservoir (i.e., ~ 3.2 W when pumping 1 Torr $\cdot$ l/sec of 80% hydrogen and 20% helium) was much higher than the amount caused by hydrogen condensation and was attributed to gas convection between LN₂ reservoir and outer LHe reservoir.

IV. CONCLUSION

Based on the performance of this cryopump during the test runs at BNL and on our previous studies on the cryocondensation pumping^{1,2} and cryosorption pumping⁷, we have reached the following conclusions:

1. The performance of this cryopump has met the designed requirements. The pumping speed and adsorption capacity for helium exceed the TSTA specifications (3,000 l/sec versus 1,500 l/sec and $>5,000$ Torr $\cdot$ l versus $>3,400$ Torr $\cdot$ l). This demonstrates that the compound cryopump is capable of evacuating the fusion reactor and separating helium from hydrogen isotopes.
2. Using coconut charcoal as adsorbent for cryosorption pumping of helium is superior to using molecular sieves. Unlike molecular sieves, no high-temperature bake will be required to condition the charcoal, and the presence of small amount of hydrogen and other impurities has little effect on the pumping speed and adsorption capacity of the charcoal.
3. The cryopump operated well at a pressure as high as 1×10^{-3} Torr with flow rate up to 5 Torr $\cdot$ l/sec. The LHe boil-off rates were much higher than those estimated from heat content and might be caused by gas convection.

Table I. Heat load and cryogen consumption rate of each reservior.

	Inner LHe Reservior		Outer LHe Reservior		LN ₂ Reservior	
	A	B	A	B	A	B
I	0.2	0.25	0.8	1.0	80	2
II	0.3	0.3	1.2	1.5	90	2
III	0.5	0.6	4.0	5.0	100	2.5
IV	0.5	0.6	4.0	5.0	100	2.5

A: heat load in watt.

B: cryogen consumption rate in ℓ /hr.

I: without any gas input.

II: with 0.3 Torr $\cdot\ell$ /sec helium flow.

III: with 1.0 Torr $\cdot\ell$ /sec helium flow.

IV: with 1.0 Torr $\cdot\ell$ /sec of 80% hydrogen and 40% helium.

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Figure Captions

Figure 1. Systematic drawing of the TSTA vacuum system.

Figure 2. The BNL-TSTA compound cryopump design.

Figure 3. Overall view of the BNL-TSTA compound cryopump.

Figure 4. Cryosorption panel made of metalized coconut charcoal plates. The thermal anchored silicon diodes are shown at center and edge of the panel.

Figure 5. Setup for testing the cryopump at BNL.

Figure 6. Helium pumping speed of the charcoal panel at various flow rate and surface coverage.

TSTA MAIN STREAM

C ORIFICE WITH 10 l/s
 CONDUCTANCE FOR H₂
 ORIFICE WITH 7 l/s
 CONDUCTANCE FOR He
 MS VARIAN QUADRUPOLE
 MASS SPECTROMETER
 TMP BALZER TURBOMOLEC-
 ULAR PUMP