Large Cryosorption Pump for the NBI Test Stand

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(Received ,2003)

Abstract— A large cryo-pumping system composed of 4 cryosorption pumps was designed and manufactured to satisfy the pressure requirements of the NBI test stand. The cryosorption pump consists of a thermal shield/baffle assembly and a cryopanel coated with activated carbon granules. The thermal shield is cooled by liquid nitrogen, and the cryopanel by a commercial helium refrigerator. The operation characteristics and vacuum performance of the cryosorption pump were investigated. The cooling down time of the cryopanel to 20 K was about 6 hours with a liquid nitrogen consumption rate of about 35 L/s. The maximum pumping speed of the cryosorption pump for the hydrogen gas measured by the steady pressure method was about 90,000 L/s.

Key Words : NBI, cryosorption pump, cooling curve, pumping speed

1. Introduction

A test stand was built for developing and examining the ion sources and beam line components to be installed in the KSTAR (Korea Superconducting Tokamak Advanced Research) NBI (neutral beam injection) system. The test stand is equipped with a 60 m^3 vacuum chamber, an ion source, and one set of beam line components (refer to Fig.1). In the test stand, the hydrogen ion beam of maximum 2.7 MW (80 keV, 35 A) will be produced with one ion source. Some fraction of the ion beam passing through the gas molecules in the neutralizer is converted to a neutral beam depending on the pressure.

To make a powerful arc discharge, the pressure of the ion source must have a proper range such as $2\times10^{-3}\sim10^{-2}$ mbar. Considering the ionization efficiency of 40~50%, the ion source must be supplied with the hydrogen gas at a rate of up to 700 sccm (1 sccm ≅0.016 mbar·L/s at 20°C) to attain the beam current of maximum 35 A (1 A=0.1265 T[K]/273 mbar·L/s=7.49 sccm) ion beam. Moreover, the gas supply rate to the neutralizer should be at least 2000 sccm to keep the average pressure in the path between the ion source and the chamber higher than 3×10^{-3} mbar, which is required to get a sufficient neutral fraction [1]. In spite of such a large gas load, the chamber pressure should be low enough not to diminish the neutral beam generated in the neutralizer.

The key point in designing the vacuum pumping system for the NBI test stand is how to evacuate the NBI chamber to the pressure of less than 10^{-4} mbar when the gas throughput is a few thousands sccm. The vacuum pump to fulfill such a requirement should have a pumping speed of around 500,000 L/s, which is nearly impossible to be attained with the conventional pump installed on a port with a finite cross section outside the chamber. The only solution to this problem is to use an in-chamber pump that can utilize the maximum pumping area available in the chamber. Cryopumps are the most probable candidate for the in-chamber pump of the NBI test stand because of their high unit pumping speed, cleanness, moderate cost, and so on.

There are, in principle, two types of the cryopump, namely a cryo-condensation pump in which hydrogen gas is pumped to the liquid helium cooled 4 K panel, and a cryosorption pump with the activated carbon (AC) coated panel cooled to 15 K by a helium refrigerator. Though it is planned to use cryo-condensation pumps in the KSTAR NBI system to be constructed at the KBSI site, the NBI test stand is operated with cryosorption pumps because the liquid helium plant is not available in the KAERI site.

In this paper, the design of the cryo-pumping system composed of 4 cryosorption pumps is described, and the test results on the operation performance and pumping characteristics of the pump are reported.

2. Structure of the cryosorption pump

The body structure of the cryosoption pump set up in the NBI test stand is in principle similar to that of the commercial one. The main components of the pump body are an 80 K thermal shield and a 20 K cryosorption panel. The whole pump body looks like a cylinder as described in Fig. 2. The thermal shield protects all the cryopanel against 300 K radiation from surrounding walls and structures. The thermal shield is practically divided into upper/lower circular plates and a cylindrical baffle that allows gas molecules to pass through and to be adsorbed on the cryopanel. The baffle consists of 50 chevron blades of 120° bending angle, each has a LN_2 hole of 5 mm diameter along the center axis of the blade. The chevron blades are placed regularly at 7.2°, and form as a whole a circular ring of 550 mm O.D and 356 mm I.D. The blades are blackened by hard anodizing to enhance the absorption of thermal radiation.

The cryopanel consists of 4 identical AC-coated rectangular plates of 145 mm×1000 mm brazed to a center rod along the long side at intervals of 90°. The surface density of the AC layer is about 500 g/m^2. All the surface of the cryopanel look directly at the baffle. Therefore, most gas molecules transmitting the baffle can reach the surface of the cryopanel without additional reflections, thus the cryopanel will be exposed to more thermal radiation.

In the commercial cryopump, the AC-coated surface is usually positioned to be out of sight of the baffle so that other gases do not hinder the pumping of hydrogen. Gas molecules such as nitrogen and carbon monoxide, which do not condensate on the 80 K baffle, will be adsorbed on the bare surface of the cryopanel facing the baffle and can rarely reach the AC-coated surface. In such a configuration the pumping speed for the hydrogen gas is apparently reduced because of the finite conductance of the path to the AC-coated surface.

The present model of the cryosorption pump for the NBI test stand was designed on the grounds that there is normally a negligible air leak that will introduce nitrogen gas molecules into the NBI chamber, and it is more important to increase the pumping speed for the hydrogen gas.

The cryo-pumping system of the NBI test stand is composed of four cryosorption pump bodies, four G-M helium refrigerators and two LN_2 bottles of 200 L each. One LN_2 bottle supplies liquid nitrogen to the two pumps. The whole view of the cryo-pumping system is shown in Fig. 3. The G-M refrigerator is installed upside down on the roof of the NBI chamber. The upper thermal shield of the pump is attached to the first stage of the refrigerator, and the center rod of the cryopanel is hung from the second stage. The baffle and the lower thermal shield are set on the frame fixed to the chamber wall, and cooled by liquid nitrogen. The mid line of the LN_2 bottle is adjusted to be comparable to the top of the baffle, and the liquid nitrogen level in the baffle blade is controlled by the weight and the vapor pressure of liquid nitrogen in the bottle.

3. Pumping speed of the cryosorption pump

The pumping speed of a vacuum pump is expressed by the multiplication of the orifice conductance C_o and the pumping probability α as follows;

$$S_P = C_o\alpha = AC\alpha \tag{1}$$

The orifice conductance is the volume flux (or unit orifice conductance) C [L/s·cm^2] times the pumping area A [cm^2]. The volume flux is defined as $v_{av}/4$, where v_{av} is the average speed of gas molecules. v_{av} is expressed as $3.64\times10^4\sqrt{T_{gas}/M}$ [L/s], where T_{gas} [K] and M are the gas temperature and the molecular mass, respectively.

Consequently, the pumping speed is approximately proportional to the square root of the gas temperature if the pumping probability is nearly independent of the gas temperature.

For the cryopump mounted on the port of the vacuum chamber, the gas temperature is well defined as the room temperature or the chamber temperature. However, for the cryopump installed inside the NBI chamber in which many cold components including LN_2 bottles are also placed, the gas temperature may be far different from the room temperature.

The pumping speed S_p can be calculated using experimentally measurable parameters, the gas pressure in the chamber P, and the gas flow rate (or throughput) to the chamber (or to the pump) q, by the equation $S_P=q/P$. If an ionization vacuum gauge, which gives the temperature-independent pressure, is calibrated with an absolute pressure gauge such as a spinning rotor gauge (SRG), the true gas pressure is given by

$$P = \frac{P_{dis} T_{gas}}{S T_0} \qquad (2)$$

where P_{dis} is the displayed pressure of the gauge controller, and S is the sensitivity (=displayed pressure÷standard pressure) of the gauge calibrated at the temperature T_0.

The gas is usually intoduced into the chamber through a mass flow controller (MFC) that controls the mass or molecule number of the supplied gas, not the throughput. The throughput q [mbar·L/s] is related with the mass flow rate Γ [sccm] defined at 0°C such as

$$q = \frac{\Gamma}{59.2} \frac{T_{gas}}{273} \qquad (3)$$

Then, from Eqs. (2) and (3), the pumping speed is finally expressed as the following equation

$$S_p = \frac{S \Gamma T_0}{16174.7 P_{dis}} \qquad (4)$$

Though this expression on the pumping speed looks explicitly independent of the gas temperature, the temperature-dependency is still incorporated in P_{dis} ($\sim 1/\sqrt{T_{gas}}$).

If an absolute pressure gauge such as the capacitance diaphragm gauge (CDG) is used to measure the chamber pressure, Eq. (2) must be changed to Eq. (5) taking into account the thermal transpiration effect.

$$P = \frac{P_{dis}}{S} \sqrt{\frac{T_{gas}}{T_{gauge}}} \qquad (5)$$

where T_{gauge} is the sustained temperature of the gauge. From Eq. (3) and Eq. (5) the pumping speed is given by

$$S_p = \frac{S\Gamma\sqrt{T_{gas}T_{gauge}}}{16174.7P_{dis}} \tag{6}$$

If the pumping speed of an external pump such as a TMP is also proportional to the square root of the gas temperature, the gas temperature is obtained by the equation

$$T_{gas} = T_{room}\left(\frac{P_{dis0}}{P_{dis1}}\right)^2 \tag{7}$$

where 0/1 means before/after cooling of the cryosorption pump.

The gas temperature can be more precisely measured by using a time controlled MFC and an absolute pressure manometer. When admitting the gas at a fixed rate and duration to keep the gas number density constant both before and after cooling of the cryopump, the gas temperature is simply given by the ratio of the displayed pressures as $T_{gas}=T_{room}(P_{dis1}/P_{dis0})$, because the pressure is proportional to both the number density of gas molecules and the gas temperature.

The transmission probability (P_t) of the particles through two chevron blades tilted at 7.2° to each other is calculated by the Monte Carlo simulation to be about 0.16, which is much lower than 0.25 for the parallel blades. If A_1, A_2 and s_H denote the outer surface area of the baffle, the area of the cryopanel, and the sticking coefficient of hydrogen gas molecules on the activated carbon, respectively, the pumping probability α is expressed as [2]

$$\alpha = P_t \frac{s_H A_2}{P_t A_1 + s_H A_2} \tag{8}$$

In the present cryosorption pump model, A_1=1.73 m^2 and A_2=1.2 m^2. If s_H is assumed to be 0.6~1, α has the value of 0.116~0.13. For example, the expected pumping speed of the cryosorption pump is calculated from Eq. (1), for the hydrogen gas (M=2) at the gas temperature of 240 K, to be 8×10^4~9×10^4 L/s.

4. Pumping capacity

The pumping capacity of the cryopump for any non-condensable gas is determined by the isotherm which shows the relationship between the adsorption quantity [mbar.L/g] of gas molecules and the equilibrium pressure at a certain temperature. Fig. 4 is an example of the isotherm of the hydrogen gas on the activated carbon for various temperatures. In the figure it is found that, at the cryopanel temperature of 20 K, if the chamber pressure should be kept below 5×10^{-5} mbar the total amount of hydrogen molecules adsorbed on the panel of 1.2 m^2 area is about 235 mbar·L/g×500 $g/m^2\times1.2$ $m^2=1.41\times10^5$ mbar·L. If assuming the pumping speed and the working pressure as 8.5×10^4 L/s and 5×10^{-5} mbar, respectively, the lifetime (or the regeneration interval) of the cryosorption pump is about 9.2 hours.

Water molecules, which are the most dominant residual gas, condensate initially on the surface of the LN_2 bottle and later on the 80 K thermal shield including the baffle. The pumping speed for the water molecules is at least 500,000 L/s with one cryosorption pump. Therefore the water peak perfectly disappears in the mass spectrum just after the LN_2 bottle is filled with liquid nitrogen. It is not too say that there is no practical limit on the pumping capacity of the water molecules because the thickness of the ice can be more than a few cm.

5. Performance test and results

The first step of the experiment is dumping liquid nitrogen in the portable LN_2 dewar to the LN_2 bottle in the chamber and turning on the helium refrigerators after roughing the chamber to a 10^{-6} mbar range by the 5500 L/s TMP. Then the baffle of the cryosorption pump is cooled by liquid nitrogen supplied from the LN_2 bottle, while the cryopanel is by the helium refrigerator. During the cooling stage the hydrogen gas is frequently introduced into the chamber, and the pressure rise and the mass spectrum are checked. The mass flow rate of the hydrogen gas controlled by the MFC is fixed at 200 sccm during the experiment. The pressure is measured with the ionization gauge calibrated by the SRG.

Though the pumping of water molecules is strongly influenced by the baffle temperature, the pumping capability for the hydrogen gas depends directly on the temperature of the cryopanel. The first impact on the pumping system observed after cooling down the baffle is a slight reduction of the pumping speed of the TMP, because the gas temperature lowers as some of the internal structures become colder than chamber walls. When a half of the cryopump system is operated, the saturated gas temperature is estimated to be 240 K from Eq. (7).

Figure 5 shows the temperature variation of the cryopanel when supplying liquid nitrogen to the baffle, and operating the refrigerator. The ultimate temperature is about 18 K, which is attained in about 6 hours after the start of cooling. Liquid nitrogen of 150

L is consumed to cool down the baffle to 80 K in 3 hours and to keep the temperature for 2 hours, and another 150 L is spent to maintain the cooling stage for 6 hours. This means that it is possible to carry out the beam extraction experiment for at least 5 hours under the full pumping speed of the cryosorption pump by the consumption of liquid nitrogen of 300 L.

The pumping speed of the cryosorption pump is shown in Fig. 5 as a function of the cryopanel temperature. The cryosorption pump starts to show its pumping capability for the hydrogen gas at a temperature around 60 K. The pumping speed is steeply increased at a temperature below 50 K and reaches the ultimate level of about 90,000 L/s at below 20 K.

6. Conclusions

A cryo-pumping system composed of four cryosorption pumps and two LN_2 bottles was designed and manufactured. The cryosorption pump consists of a thermal shield/baffle assembly cooled by liquid nitrogen, and an AC-coated cryopanel cooled by a commercial helium refrigerator.

Liquid nitrogen of 300 L was consumed to cool down the baffle to 80 K in 3 hours and to keep the temperature for 8 hours. During the period of cooling, the cryopanel reaches the ultimate temperature of about 18 K in about 6 hours after turning on the refrigerator.

The pumping speed of the cryosorption pump was measured by the steady pressure method. The pump started to show its first pumping capability at a temperature of 60 K. The pumping speed was steeply increased at a temperature below 50 K and reached the ultimate level of about 90,000 L/s at below 20 K.

Besides lowering the chamber pressure tremendously, the use of the in-chamber cryosorption pump in the NBI test stand made the time constant of the gas fueling and/or the pumping system shorter to below 1 sec, otherwise it would be longer than 1 minute.

References

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[2] S. R. IN, M. Y. Park, J. Kor. Vac. Soc. 12, 86(2003)

Figure Captions

1. Whole view of the NBI test stand.
2. Structure of the cryosorption pump.
3. Configuration of the cryo-pumping system.
4. Isotherm of H_2 on the activated carbon at cryogenic temperature.
5. Cooling curve of the cryosorption pump.
6. Pumping speed of the cryosorption pump for H_2.