Maintenance of the 1st NBI vacuum system for the KSTAR tokamak

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Abstract. First neutral beam injection system for the KSTAR tokamak has been operated after the installation and commissioning on 2010. To provide 120 keV and more than 6 MW deuterium neutral beam, it requires large vacuum pumping system with the pumping speeds 1.0E6 l/s range. For this purpose, R&D works with a prototype cryosorption panel had performed from Korea Atomic Energy Research Institute (KAERI) and GM cooler based 2 stage cryosorption pump was accepted for the 1st NBI system. During 10 years of annual operation, the pumping speeds decreased continuously due to the damage in cryopanels and all of the cryopanels were repaired for the 2021 KSTAR campaign. Details of the 1st KSTAR NBI vacuum pumping system will be introduced and long operation results including the behavior after the repair, will be reported in this paper.

1. Introduction

First neutral beam injection system for the KSTAR (Korea Superconducting Tokamak Advanced Research) facility plasma experiments has been operated until now (2021) according to the annual plasma operation plan after the successful commissioning on 2010 [1,2]. Figure 1 and 2 show side view of the 1st neutral beam injector (NBI-1) and 3-dimensional layout of the cryosorption pumping module, respectively. The length, height, and width of the main cryostat are 5 m, 4 m, and 3 m, respectively. It consists of 3 ion sources, 2 neutralizing sections, an ion beam bending magnet (BM), an ion dump, a movable calorimeter, and so on. Deuterium gases injected to the ion sources are ionized and accelerated by the grids charged with 100 kV electrical potential. Around 40~50% of D+ ions expected to be neutralized by passing 2 neutralizing sections and the beams, with the beam power 6 MW in maximum, are to be supplied to the tokamak for the plasma heating. Whereas, remained ions passing the BM lost their ion energy at the water-cooled ion dump.

Up to 3,000 sccm of D2 gases shall be injected into the NBI-1 to maintain deuterium D2 gas neutralization efficiency and to produce beam power as mentioned above [3]. Moreover, the vacuum pressure of the NBI cryostat shall maintain 1.0E-5 mbar range even in such amounts of gas injection to minimize the reduction of the neutralization efficiency. Therefore, large vacuum pumping system that has a D2 gas pumping speeds more than 1.0E6 liter/sec is required for the NBI-1. For this purpose, preliminary R&D works about the cryosorption pump had accomplished from KAERI (Korea Atomic energy Research Institute), Korea as a KSTAR NBI project [3~5]. Based on the Monte Carlo simulation, KAERI members developed a prototype cryopanel and tested [3]. The important KAERI’s R&D results are summarized in Table 1.
In general, the effective vacuum pumping speeds $S_p$ of a cryo-sorption pump can be estimated from the equations 1 to 3 \cite{2,6,7}, where $C_o$, $\alpha$, $C$, $A$, $v_{av}$, $T$, and $M$ are, respectively, orifice conductance, pumping probability, orifice conductance per unit area, pumping surface area, average gas velocity, temperature, and molecular mass number in MKS unit.

\begin{equation}
S_p = C_o \alpha = C A \alpha
\end{equation}

\begin{equation}
C = \frac{v_{av}}{4}
\end{equation}

\begin{equation}
v_{av} = 145.51 (T/M)^{0.5}
\end{equation}

Considering both of the Monte Carlo simulation and test results, KAERI members concluded the pumping probability to be 0.142 (Table 1). Since the design value of the NBI-1 cryopanel surface area $A \sim 25.6 \text{ m}^2$, the vacuum pumping speeds of $\text{H}_2$ and $\text{D}_2$ gases, are expected to be $1.62\times10^6 \text{ liter/sec}$ and $1.15\times10^6 \text{ liter/sec}$, respectively.

**Figure 1.** Side view the KSTAR 1$^{st}$ NBI. 1: ion source, 2: neutralizer, 3: bending magnet, 4: ion dump, 5: movable calorimeter, 6: cryosorption pump section operating by 2 stage GM (Gifford-MacMahon) cycle refrigerator, 7: main gate valve connected to the KSTAR tokamak, 8: NBI main cryostat roughing pumps, 9: turbo-molecular pump for the main cryostat, and 10: turbo-molecular pump for the ion source.

**Figure 2.** Three-dimensional view of the cryosorption pump module. 1: cryopanel, 2: Chevron baffle with 120$^\circ$ angle blades (beam line side), 3: thermal shields (cryostat wall side), and 4: cold head of the 2 stage GM cooler.
Table 1. Preliminary R&D results of the KAERI

| Parameter, unit                      | Value |
|--------------------------------------|-------|
| Angle of Chevron baffle blade, deg.  | 120   |
| Pumping probability, non             | 0.157 |
| Sticking coefficient at 20 K, non    | 0.4   |
| $\text{H}_2$ gas pumping speeds, liter/sec-m$^2$ | 6.82E4 |
| $\text{D}_2$ gas pumping speeds, liter/sec-m$^2$ | 4.47E4 |
| Cryogenic loads to a cryopanel, W     | 12.7  |

Based on above R&D works, three-dimensional design of the cryosorption pump module was finalized (Fig. 2). Each module is located in the main cryostat side wall boundary (Fig. 1). In one module, there are 8 sets of cryopumping stations. Totally 16 sets of cryopanels and GM coolers were manufactured and supplied from the company ULVAC, Japan. Both side of each aluminium cryopanel coated with activated carbon using a glue. But, details of coating methods and information of the used glue is not opened from the company. Operating temperature of the GM cooler cold head and average temperature of the 2 m long cryopanel are, respectively, 12 K and 16 K on the assumption that the liquid nitrogen cooled baffle and thermal shields temperatures ~ 80 K. The 1st stage cold head temperature is 50 K and it is thermally anchored to the top thermal shields.

2. System set-up and maintenance

Figure 3 shows the process and flow diagram of NBI-1 vacuum pumping system including liquid nitrogen cooling circuits for the thermal shields and Chevron baffle. For the main cryostat with the volume 60 m$^3$, one set of 600 m$^3$/hr roughing pumping system and three TMPs (Turbo Molecular Pumps) with total pumping speeds 6,000 liter/s are mounted. The TMPs have a role of vacuum pumping the main cryostat bellow 1.0E-4 mbar before the start of cryopumping system cool-down and pump out of the $\text{D}_2$ gasses in the cryopanel regeneration stage. For each OMA (Optical Multi-channel Analyzer) chamber consisted with an ion source and a neutralizer, one set of serially connected TMP and dry-pump with the pumping speeds 2,000 liter/sec, is mounted. After the cool-down of the Chevron baffle and thermal shields to liquid nitrogen temperatures, the cryopanels are to be cooled down to 16 K in average.

![Figure 3. Process and flow diagram of the NBI-1 vacuum pumping system.](image-url)
In the 1st commissioning stage on 2010, the vacuum pumping speeds were higher than 1.0E6 liter/s. However, the pumping speeds were decreased continuously meanwhile 10 years of operation because lots of the vacuum faults took place. The root cause of the degradation was the splitting of the activation carbon granules from the cryopanels due to the water leakage in the main cryostat and OMA chamber (Table 2 and Fig. 4). As a result, the vacuum pumping speeds reduced to 5.0E5 liter/sec when it checked after the 2019 KSTAR campaign. However, there had been no severe impact to the neutral beam injection because the amount of D$_2$ gas injection was low (less than 1,600 sccm). One half of the cryopanels (8 sets) were repaired before the KSTAR campaign 2020 and rest 8 sets before the campaign 2021 to recover the vacuum pumping speeds.

| Year | Water leakage accidents                      |
|------|---------------------------------------------|
| 2011 | Bottom area of the calorimeter              |
| 2013 | Water cooled beam scraper of the ion source No. 2 |
| 2014 | Bellows for the G1 grid of the ion source No. 3 |
| 2015 | G1 grid of the ion source No. 3             |
| 2016 | G4 grid of the ion source No. 2             |
| 2016 | Swilling tube of the ion dump               |
| 2018 | Neutralizer No. 2 and calorimeter           |

Figure 4. Splitting of the activated carbon.

3. Performance tests after the maintenance

Figures 5~8 show the performance test results of the cryosorption pumping system after the maintenance in 2021. D$_2$ gases were injected into the main cryostat with 500 sccm step and up to 3,000 sccm (Fig. 5). The gas injection pulse duration was maintained more than 5 minutes take into accounting the long pulse (> 320 sec) plasma operation scenario. Meanwhile, the vacuum pressure of the main cryostat was measured (Fig. 6).

At the beginning of gas injection, the vacuum pressures increased to a peak value and decreased exponentially, after on. To obtain saturated vacuum pressure \( P_s \), each vacuum curve was plotted with exponential decay function as \( P_s + P_1 \exp(-t/\tau) \). And then, the value of \( P_s \) converted into D$_2$ gas pressure by dividing with the gas correction factor 0.35 [8]. The value of gas injection was plotted as a function of saturated D$_2$ gas pressure to obtain the cryosorption pumping speeds, finally (Fig. 7). Obtained vacuum pumping speed was 1.1E6 liter/s and it means full recovery of the vacuum pumping performance.
Figure 5. Graph of $D_2$ gas injection.

Figure 6. Graph of main cryostat vacuum pressure.
Figure 7. Graph for the pumping speeds calculation.

Figure 8. Cryopanel temperature variation according to D$_2$ gas injection (from 500 to 3,000 sccm). Open square; nearby cold head, open circle; bottom of the cryopanel.
The cryopanel temperatures were measured to check the variation during the performance tests (Fig. 8). Peak temperatures were increased proportional to the gas injection values. At the gas injection from zero to 3,000 sccm, the temperature differences on the top and bottom areas of the cryopanels were reached to 1 K and 2 K, respectively. However, these experiments were done without long pulse ion beam acceleration. Moreover, the liquid nitrogen cooled baffle and thermal shields temperatures were in the 90~100 K range (higher than 80 K design value) because the liquids were transferred with high pressure (5~6 bar) take into accounting long pipe line length more than 100 m. Therefore, above two issues need to be checked and improved for the near future full power (6 MW) gas injection.

4. Concluding remarks

In this paper, it was introduced the R&D works in the development of large vacuum pumping system for the KSTAR NBI-1. During 10 years of annual operation, the vacuum pumping speeds reduced by one half (5.0E5 liter/s) due to water leakages and enhanced activated carbon splitting. For the improvements, it requires R&D for the glue resistant to water vapor. ITER has some improvements by applying ceramic glue, instead of conventional one applying in many cryopanel producing company [9]. However, it is not clear whether the ceramic glue is resistant to water or not. After the repair, the pumping speed was recovered to 1.1E6 liter/s. Regarding high beam power NBI operation, it needs to be improved in the liquid nitrogen cooling circuits. Application of a commercial 77 K liquid nitrogen cold pump which has MTBM (mean time between maintenance) longer than 2 years could be one of solution.

5. References

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