Simulation Analysis of the Design of a Vacuum Pumping System for the Closed Helical Divertor in the Large Helical Device*)

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A promising candidate of a vacuum pumping system for the closed helical divertor in the large helical device is proposed using a three-dimensional neutral particle transport simulation code (EIRENE) and a finite element based multi-physics analysis software (ANSYS). It shows that heat load on a gas/liquid He cooled panel by thermal conduction due to high energy neutral hydrogen atoms is dominant over that by radiation from divertor plates heated by the LHD peripheral plasma. It proves that optimization of the configuration of the vacuum pumping system can significantly reduce the heat load on the panel without serious degradation of the pumping efficiency.

Keywords: closed divertor, LHD, pumping system, neutral particle transport, EIRENE, ANSYS, peripheral plasma

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1. Introduction

Neutral particle control in the plasma periphery is a major concern for sustaining ICRF heated long pulse discharges, Super Dense Core (SDC) plasmas, and high ion temperatures in the Large Helical Device (LHD) [1–3]. For solving this issue, two modules of a Closed Helical Divertor (CHD) without pumping systems were installed in the inboard side of the torus. The CHD consists of slanted divertor plates, a dome structure, and target plates, by which neutral particles released from divertor plates are effectively confined behind the dome [4]. A neutral particle transport code (EIRENE) predicts that the CHD enhances the neutral particle density in the inboard side of the torus by more than one order of magnitude compared to that in the original open divertor configuration [5].

In order to achieve efficient particle control, a vacuum pumping system such as a cryopump will be installed behind the dome along the space between two helical coils in the inboard side of torus. Because the cryopump faces the divertor plates and the peripheral plasma (primary sources of high-energy neutral particles and radiation), it is essential to eliminate the heat load on the cryopump without serious degradation of particle pumping efficiency. A pumping system, which consists of water cooled (WC) blinds/chevrons, liquid nitrogen (LN_2) cooled chevrons and gas/liquid helium (LHe) cooled panels, was proposed. Neutral particles are absorbed on the surface of the LHe cooled panel which is surrounded with the LN_2 cooled chevrons in order to suppress radiation loss from the panel. The WC blinds/chevrons enclose the LN_2 cooled chevrons for protecting them from radiation released from divertor plates and the peripheral plasmas. In this paper, a promising candidate of the vacuum pumping system is proposed by optimizing the configuration of the WC blinds/chevrons, etc.

2. Optimization of the Configuration of Water Cooled Blinds/Chevrons

There are two candidates of the water cooled components for protecting the LN_2 cooled chevrons: WC blinds/chevrons. The particle pumping efficiency in both cases was investigated using the neutral particle transport code in a simple cubic grid model as shown in Fig. 1. Test particles (neutral hydrogen molecules) are launched

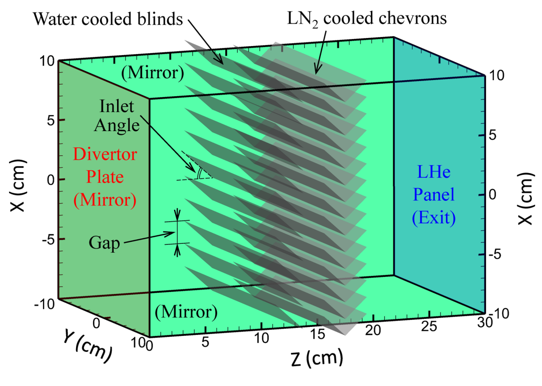

Fig. 1 A simple cubic grid model for neutral particle transport simulation to analyze the particle pumping efficiency in a case with WC blinds.

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Table 1 Ratios of the molecular hydrogen density at the LHe cooled panel to that at the divertor plate.

	Ratio ($n_{H2}^{LHe}/n_{H2}^{Div}$)
with WC chevrons	0.1125
with WC blinds (Gap = 13 mm)	0.1337
with WC blinds (Gap = 17 mm)	0.1480
with WC blinds (Gap = **37** mm)	**0.1589**
with WC blinds (Gap = 77 mm)	0.1493
w/o WC blinds/chevrons	0.1202

from the left side (divertor plate) with an energy corresponding to 800 K. The right side (LHe cooled panel) is an exit, and the other surfaces are treated as mirrors. The surface temperatures of divertor plates (mirror), the WC blinds/chevrons (steel) and LN_2 cooled chevrons (aluminum) are assumed to be 1073 K, 300 K, 70 K, respectively. Table 1 gives the calculations of the ratio of the molecular hydrogen density at the LHe cooled panel (n_{H2}^{LHe}) to that at the divertor plate (n_{H2}^{Div}) in six different configurations (only WC components are changed). The ratio is an indicator of the particle pumping efficiency; the higher ratios mean enhanced pumping efficiencies. The ratio in the case with the WC blinds is higher than that with the WC chevrons. It is interesting that the ratio without WC blinds/chevrons is lower than that in the case with the blinds, indicating that the WC blinds contribute to enhancing the particle pumping efficiency. By tracking many test particles in the simulation, it is found that the WC blinds have a function to repel neutral particles, which are reflected on the LN_2 cooled chevrons, to the LHe panel (right), enhancing particle pumping. When the gap of the WC blinds is 37 mm, the maximum ratio of the neutral particle densities is achieved, which indicates that the most efficient particle pumping is realized in this configuration. Thus, WC blinds with an optimized gap are adopted to one of the primary components of the pumping system.

The dependence of the ratio ($n_{H2}^{LHe}/n_{H2}^{Div}$) on the size of the WC blinds was also investigated, showing no observable change of the pumping efficiency under a constraint that the blinds make the LN_2 cooled chevrons not to face the divertor plate. The investigation of the dependence of the pumping efficiency on the angle of the blinds also indicates that it does not significantly change with the blind angle under the above-mentioned constrain unless quite closed inlet angles of the blinds.

3. Modeling of the Vacuum Pumping System

The configuration of the CHD which is viewed from the outboard side is illustrated in Fig. 2 (a). In order to investigate behavior of neutral particles in the pumping system for the CHD, a grid model for the configuration of the pumping system was created as shown in Fig. 2 (b). The geometry of this model simulates the two-dimensional

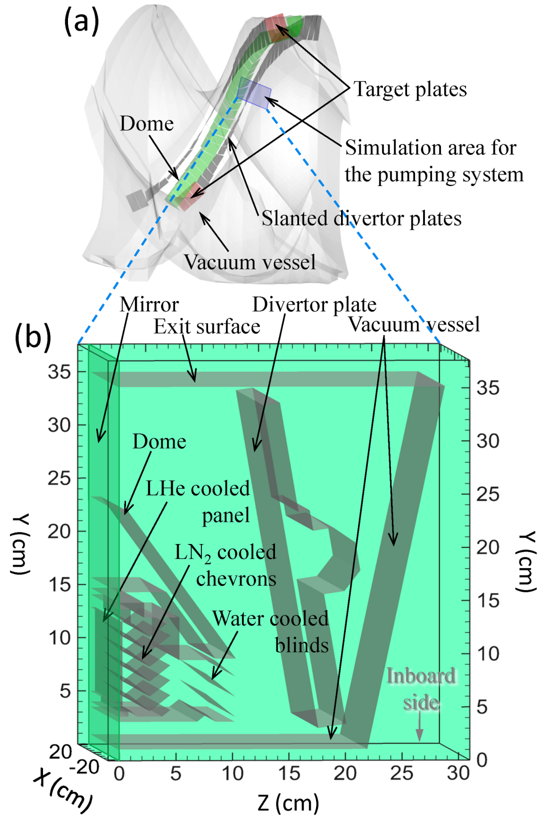

Fig. 2 (a) The configuration of the CHD which is viewed from an outboard side. (b) A grid model simulating the pumping system in the CHD for the neutral particle transport simulation.

cross-sectional area of a half part of the pumping system in the inboard side of the torus (a shaded rectangular frame in Fig. 2 (b)). In this model, the particle recycling coefficient on the divertor plates is unity, and the surface temperature of the dome (carbon) and the vacuum vessel (steel) is 300 K. The horizontal angle of the WC blinds is inclined toward the inboard side of the torus for protecting LN_2 cooled chevrons from a heat load by radiation from the divertor plate. Most of neutral particles entering through the blinds are reflected particles on the vacuum vessel, contributing to reduction of a heat load on the chevrons because the energy of neutral particles released from the divertor plate is reduced by particle-wall interactions. The calculations of the heat load in this model give higher estimations because of the shortest distance between the pumping system and the neutral particle source (divertor plate) in the LHD vacuum vessel.

Test particles (neutral hydrogen atoms/molecules) are launched from the divertor plate. The species, the energy and the direction of the test particles are determined by the TRIM code. The plasma parameters (T_i, T_e and n_e) on the divertor legs are set to be typical values in the LHD plasma periphery (30 eV, 30 eV and 1.0×10^{13} cm^{-3}, respectively). Particle absorption on the divertor plate and the vacuum vessel is not included. In order to consider energy interactions between neutral hydrogen molecules and vacuum components expediently, a new parameter $R_{\rm ref}$ is introduced. When a hydrogen molecule reaches to the surface of a vacuum component, a normalized uniform random number ρ is generated in the simulation. If the number ρ is larger than $R_{\rm ref}$, the energy of the hydrogen molecules is set to an energy corresponding to the temperature of the vacuum component. Otherwise, the energy of the molecules is not changed. In this simulation, the parameter $R_{\rm ref}$ is set to be 0.80, and the angular distribution of the molecules emitted from the surface follows the cosine law. In the case where a hydrogen atom reaches to a surface, the following two processes are randomly selected depending on the particle reflection ratio calculated by the TRIM code. One is that the atom is reflected on the surface with an energy and an angle determined by the code. Another one is that a molecule with a reduced statistical weight is released with an energy corresponding to the surface temperature. The upper edge in the grid model is regarded as an exit, and the left edge is treated as a mirror to simulate the symmetrical geometry of the pumping system.

4. Calculation of the Heat Load on the Vacuum Components of the Pumping System

Two physical mechanisms of heat transmission exist in the pumping system. One is radiation from the divertor plates heated by the LHD peripheral plasma, and another one is conduction due to neutral particles released from the divertor plates. The heat load deposition profile due to radiation was calculated by a finite element based multi-physics analysis software (ANSYS) using a two-dimensional model in which the configuration is the same as that for the neutral particle transport code. The emissivity of the divertor plates, the dome, the vacuum vessel, the WC blinds, the LN_2 cooled chevrons, and the LHe cooled panel are set to be 0.8, 0.8, 0.2, 0.9, 0.9, and 0.2, respectively. The total (full torus) heat loads by radiation on the WC blinds, the LN_2 cooled chevrons and the LHe cooled panels are calculated to 6.62×10^4, 3.68×10^3, 1.42×10^1 W, respectively. Analysis by the neutral particle transport code shows that the total heat loads by conduction on the three components are 2.86×10^5, 2.85×10^4, 1.40×10^3 W, respectively. In this calculation, the total current of absorbed neutral particles on the LHe cooled panel is set to be 1×10^4 A which is the highest requirement for the pumping system during repetitive pellet injection. The effect of the heat of condensation on LHe cooled panel (~30 W) is negligible. It shows that the heat load by conduction due to neutral particles is dominant over that by radiation from the divertor plates.

5. Heat Load Reduction by Optimizing the Configuration of the Pumping System

From the view point of reducing the cost of a refrigerator for the LHe cooled panel, the most critical issue is reduction of the heat load by conduction due to neutral particles. By comparing the calculations of the heat load with and without reflection of neutral hydrogen atoms on surfaces of the vacuum components using the grid model (Fig. 2 (b)), it is found that a major contribution of the heat load is relatively high-energy (> 1 eV) neutral hydrogen atoms reflected from the divertor plates. In this simulation, the surfaces of the vacuum vessel and the WC blinds are assumed to be fully covered with carbon layers which are sputtered from the divertor plate. The simulation indicates that the carbon layers contribute to reduction of the heat load on the panel by less than a factor of 2.

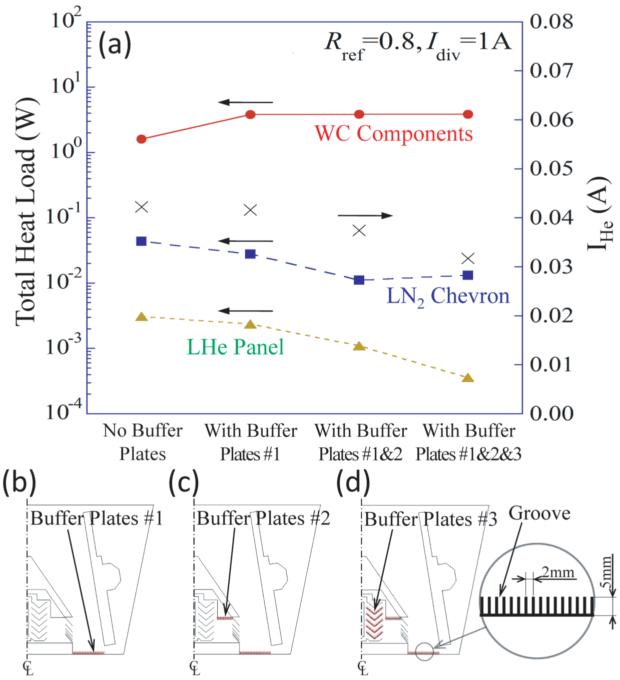

Fig. 3 (a) Heat loads on the three components of the pumping system for $I_{\rm div}$ = 1 A and the current of neutral particles absorbed on the He cooled panel in four different configurations. (b) The schematic figures of the pumping system with buffer plates #1, (c) with buffer plates #1&2, and (d) with buffer plates #1&2&3.

With a view to further reduction of the heat load, arrangement of the WC blinds is partially modified and a new component ‘buffer plate’ is introduced. There are many deep grooves (5 mm in depth, 2 mm in width and pitch) on the surface of the plate to cause multiplex reflection of neutral particles for effective energy reduction. The buffer plate is assumed to be fully covered with carbon layers. Figure 3 (a) indicates the heat load on the three components of the pumping system. In this calculation, the flow current from the plasma to the divertor plate ($I_{\rm div}$) is set to be 1 A. In the case where a buffer plate #1, which is one of WC components and fully covers the surface of the vacuum vessel in the inboard side of the torus, is installed as shown in Fig. 3 (b), the heat loads on the LN_2 and LHe

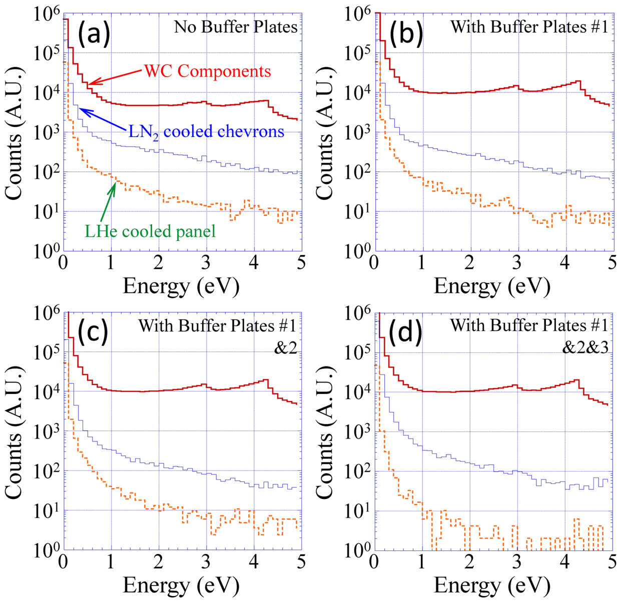

Fig. 4 (a) The energy spectrum of neutral particles heating the three components for the closed helical divertor in the case without buffer plates, (b) with buffer plates #1, (c) with buffer plates #1&2, and (d) with buffer plates #1&2&3.

cooled components are reduced by a factor of ~ 1.5 compared to those without the buffer plates while the total heat load on the WC components increases by a factor of ~ 3. The increase of the heat load on the WC components indicates that the energy of neutral particles released from the divertor plate is effectively deposited on the buffer plate. The heat loads on the LN_2 and LHe cooled components are further reduced by installing an additional buffer plate #2 on the surface of the top structure of the WC blinds (Fig. 3 (c)). The heat load decreases by more than a factor of ~ 3 compared to that without the buffer plates. It shows that the additional buffer plate reduces further the heat load on the LN_2 cooled chevrons and the LHe cooled panel. Significant reduction of the heat load on the LHe cooled panel is expected by installing buffer plates #3 on the surface of the LN_2 cooled chevrons (Fig. 3 (d)), which shows reduction by about one-order of magnitude compared to that without the buffer plates. The simulation with the buffer plate #3 shows the slight increase of the heat load on the LN_2 cooled chevron, which indicates enhancement of the deposition of the energy of neutral particles on the LN_2 cooled chevron by the multiplex reflection. It contributes to the reduction of the heat load on the LHe cooled panel.

Crosses in Fig. 3 (a) are the current of the neutral particles absorbed on the LHe cooled panel (I_{He}), which represents the pumping efficiency. It shows no serious degradation (~ 20%) of the pumping efficiency by installation of the buffer plates, which is favorable for significant reduction of the heat load with efficient particle pumping efficiency.

Figure 4 (a)-(d) show the energy spectrum of neutral particles heating the three components of the closed helical divertor in the cases without buffer plates, with the buffer plate #1, with the buffer plates #1&2, and with the buffer plates #1&2&3, respectively. The energy spectrum of neutral particles heating the WC components goes up by installation of the buffer plate #1. It shows that number of neutral particles heating the WC components increases with the installation of the buffer plate because of the extension of the WC components to the surface of the vacuum vessel in the inboard side of the torus. Figure 4 (b) and (c) indicate that the two buffer plates are effective for diminishing the energy deposited on the LN_2 cooled chevrons by reduction of relatively high energy neutral particles (> 1 eV). Figure 4 (d) demonstrates that the buffer plate #3 contribute to reduction of the number of high energy neutral particles deposited on the LHe cooled panels, showing that enhanced multiplex reflection on the LN_2 cooled chevrons due to installation of the buffer plates is useful for diminishing the heat load on the LHe cooled panels.

6. Summary

For designing a promising candidate of a vacuum pumping system for the closed helical divertor, a pumping system which consists of water cooled blinds/chevrons, LN_2 cooled chevrons and LHe cooled panels was investigated by a neutral particle transport simulation code, etc. It proves that the WC blinds with an optimized gap can enhance of the particle pumping efficiency. Analyses using a grid model simulating the configuration of the pumping system for the CHD show that the heat load on the LHe cooled panel by conduction due to neutral particles is dominant over that by radiation. Neutral particle transport simulation predicts that the buffer plates reduce the heat load on the LHe cooled panel by one-order of magnitude compared to that without buffer plates by reducing the number of relatively high energy neutral particles (> 1 eV). It successfully presents a promising candidate of the vacuum pumping system for the CHD without serious degradation of the pumping efficiency.

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