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Fully Three-Dimensional Simulation of Neutral Particle Transport in the Plasma Periphery on the Large Helical Device

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Abstract

Fully three-dimensional simulation of neutral particle transport is applied to analyses of the density profiles of neutral hydrogen in the plasma periphery and in the divertor region on the large helical device (LHD). For considering the three-dimensionally complicated geometry of the LHD plasma and the vacuum vessel, a detailed three-dimensional grid model is formed. In order to simulate the effect of the full toroidal geometry of the plasma, a new wall 'warp wall' is introduced. The calculations of three-dimensional profile of neutral densities in the grid model prove the availability of the warp walls for detailed analyses of neutral transport. The simulation strongly suggests that baffle plates installed in the inner region located between two helical coils in the vacuum vessel are cost-effective in achieving divertor detachment and efficient particle removal and control in the plasma periphery.

Keywords:

neutral particle transport simulation, Large Helical Device, divertor

1. Introduction

One of the experimental objects in the Large Helical Device (LHD) is to demonstrate the effect of helical divertor configurations for reduction of heat load on divertor plates due to divertor detachment, and suppression of impurities in the main plasma, *etc*. In the next experimental phase (Phase II), modification of the divertor configuration (change from the present open divertor configuration to a closed one) is planned [1]. An LHD vacuum vessel has larger space for the divertor compared to that in modular coil configurations such as W7-X and W7-AS, *etc* [2,3]. It enables more flexible design of the closed divertor (*e.g.* the shape and size of baffle plates and the position for vacuum pumps, *etc.*).

In Tokamaks, the density of neutral particles (molecules) in the divertor region is one of the most essential parameters for achieving divertor detachment and efficient particle/impurity removal in the plasma periphery [4]. Conventionally, two-dimensional neutral transport simulation codes have been widely applied to analyses of neutral particles, which is reasonable because of the almost toroidal symmetry of Tokamak systems. However, fully three-dimensional codes are indispensable in non-axial symmetric systems such as LHD. For this purpose, we have applied a fully three-dimensional neutral transport simulation code (DEGAS ver. 63) to the analyses of the neutral particles in the divertor region [5]. In this paper, the effect of the closed divertor configuration on neutral particle transport will be investigated by including the effect of the full toroidal geometry of the LHD plasma into the code.

2. Neutral particle transport simulation in LHD plasmas

For neutral particle transport analyses, several simulation codes have been developed and widely used for toroidally symmetric plasma confinement systems [6,7]. In these codes, test particles that represent neutral particles such as hydrogen atoms and molecules are launched from neutral gas sources (gas puffers and divertor plates, *etc.*) into a grid model which simulates the shape of vacuum vessels and plasmas. The trajectories of these particles are determined by the Monte-Carlo method based on experimental or theoretical databases of neutral-plasma/plasma-wall interactions [8,9]. The application of the simulation code to the toroidal symmetric systems has lead to development of the two-dimensional simulation code assuming the symmetry for simple and fast calculation algorism to trace test particle trajectories.

We have successfully developed a three-dimensional simulation code for the analyses of neutral particle density in the LHD plasma during local gas puffing [6]. The LHD vacuum vessel and plasma in our three-dimensional code consist of triangles and tetrahedrons, respectively. Plasma parameters (electron density (n_e), ion density (n_i), ion and electron temperature (T_i, and T_e)) and rate coefficients of

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plasma-neutral interactions inside of each tetrahedron are assumed to be constant. The profile of the plasma parameters in the grid model is defined on the bases of experimental data measured with LHD plasma diagnostic systems [10]. The rate coefficient of the interactions and the velocity components of the reactants are dependent on the plasma parameters at the location of the test particles. The correlation of a test particle position with a vacuum wall or a plasma grid in the three-dimensional model is investigated by using a database of plasma and vacuum wall geometries. The shape of the vacuum vessel and plasma are complicated, which restrains the fabrication of the full toroidal model ($0 < \phi < 360$ degrees; ϕ is a toroidal angle) due to the finite memory sources and CPU power in our computer. To overcome this restriction, we introduce a new wall 'warp wall' into the grid model. When a test particle reach the warp wall located at both toroidal ends in the grid model, the position and the direction of the test particle are changed on the bases of the geometry of the end wall. The change of the above two parameters are determined such that the test particle escaping from a toroidal end wall returns from another end wall with keeping the absolute velocity and the injection angle against the wall. Setting the warp wall at both toroidal ends in the grid model, we can effectively consider the effect of the full toroidal geometry on neutral particle transport by using a grid model for only one toroidal pitch angle ($0 < \phi < 36$ deg.) except for toroidally local gas fueling cases.

3. Calculations of neutral particle densities in the divertor region

A particle trajectory analysis by tracing magnetic field lines from just inside of the last closed magnetic surface (LCMS) with a random walk process predicts a three-dimensionally complicated particle deposition pattern on divertor plates installed in the vacuum vessel [11]. In our simulation code, we assumed that the release rate of hydrogen molecules from divertor plates is proportionally dependent on the density of the calculated particle deposition on the divertor plates. The calculation of the above particle tracing shows that the particle deposition is periodically distributed at one toroidal pitch angle interval, which enables to analyze the neutral density profile by using the grid model for one toroidal pitch angle with the warp walls. Experimental results measured with thermocouples and ion saturation currents detected with electro-static probes embedded in divertor plates support the calculation of the above particle trajectory analysis [12]. High neutral density is expected near divertor plates installed in high particle deposition areas. A tangentially viewing Charge Coupled Device (CCD) camera with an interference filter for observing an H_a emission near divertor plates detected high H_a intensity near the high particle deposition area. The above three experimental results qualitatively support our assumption that the neutral particle (hydrogen molecules) release rate from divertor plates depends on the calculation of the particle deposition pattern.

We calculated the three-dimensional profile of neutral densities (hydrogen atoms and molecules) in the LHD vacuum vessel for typical neutral beam injection (NBI) heated hydrogen plasma in an inward magnetic axis configuration (a magnetic axis position R_{ax} of 3.60 m). Figure 1 shows a three-dimensional grid model for simulating the vacuum vessel and plasma for one toroidal pitch angle. We defined the profile of the plasma parameters inside the LCMS as the measurements. The parameters outside the LCMS are estimated on the basis of a typical experimental result locally measured with a fast-moving Langmuir probe and Thomson scattering by assuming no poloidal variations. With regard to the three-dimensional profile of the plasma parameters on divertor legs, we assume that the electron temperature equals to the ion temperature, and the plasma density linearly depends on the calculated density of particle deposition pattern on the divertor plates. The absolute plasma density on the divertor legs is determined by normalizing the density to experimental data measured with the electro-static probes at a divertor plate.

Thin lines in the grid model shown in Fig. 1 represent the trajectory of the test particles released from the strike point on the divertor plates. Conventionally, a mirror wall, which reflects the test particles on the basis of the principle of specular reflection, has been widely used to simulate the full toroidal geometry in the grid model. For confirming the availability of the new warp walls on the calculation, the density profile of neutral hydrogen molecules is compared in

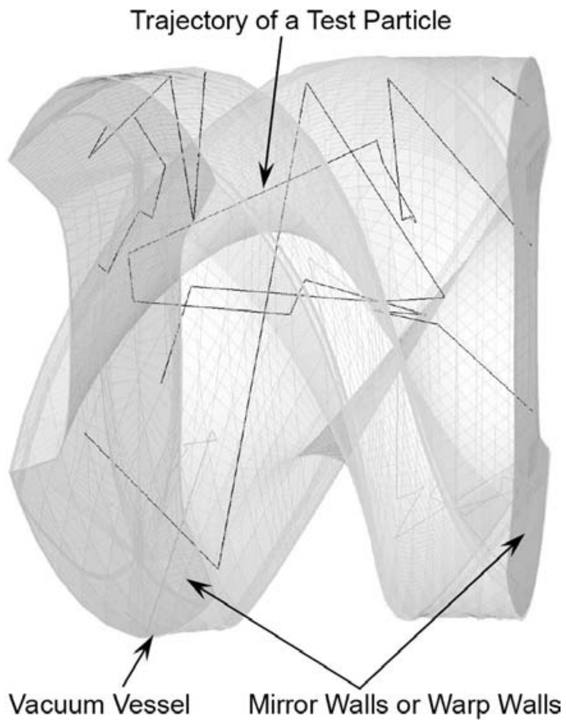

Fig. 1 Three-dimensional grid model for neutral transport simulation in the LHD plasma and the vacuum vessel for one toroidal pitch angle. Thin lines in the grid model are trajectories of a test particle emitted from the strike point on a divertor plate.

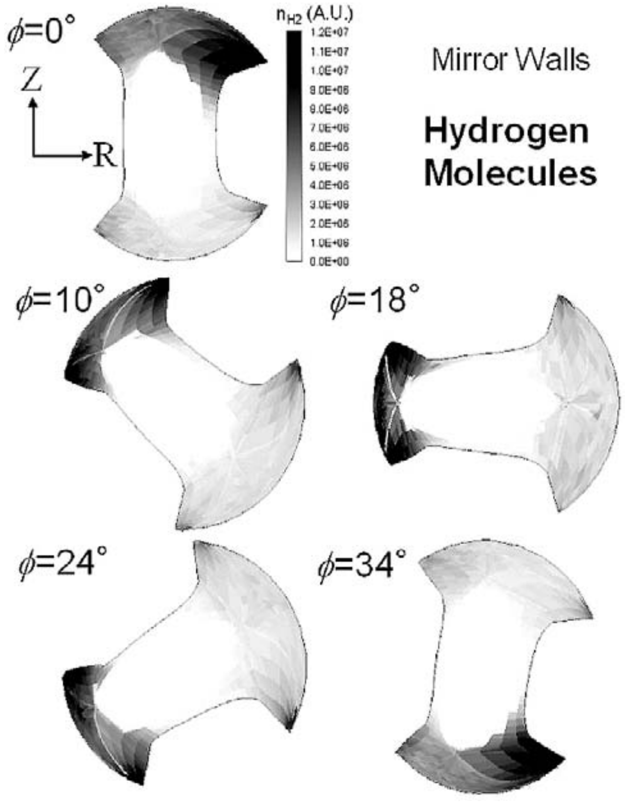

Fig. 2 Five toroidal cross sections of the density profile of neutral hydrogen molecules when the mirror walls are used at both toroidal ends of the grid model.

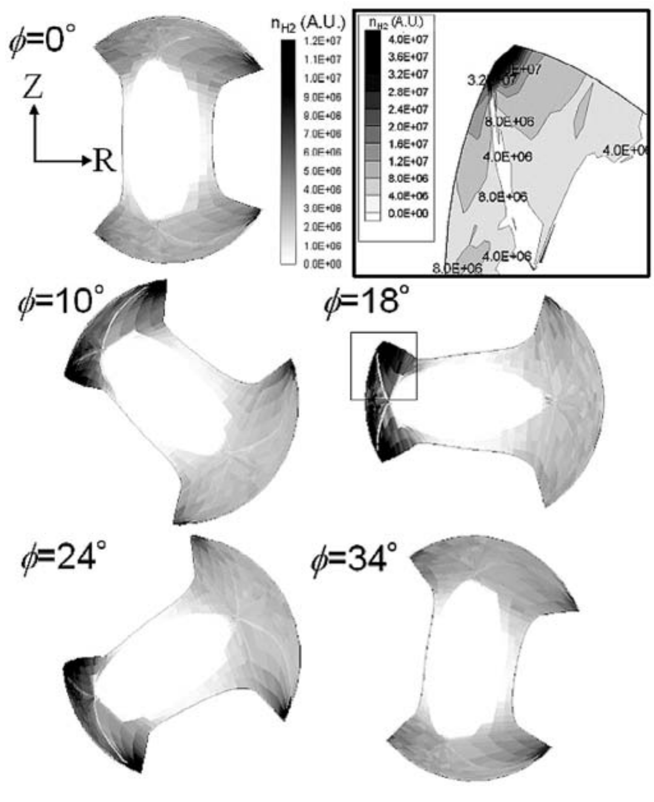

Fig. 3 Five toroidal cross sections of the density profiles of neutral hydrogen molecules when the warp walls are used at both toroidal ends of the grid model. Upper right illustration shows the enlarged contour plot of the density profile in inner divertor region.

the case where both toroidal ends of the grid model are the mirror walls and the warp walls, respectively. Figure 2 illustrates the five toroidal cross sections of the density profiles of neutral hydrogen molecules between one toroidal pitch angle (ϕ = 36 deg.) in the case of mirror walls. The high density of molecular hydrogen in the inner region in the vacuum vessel (ϕ = 18 deg.) can be explained by the facts that the density of the particle deposition on the divertor plates is significantly high in this region, and the released neutral hydrogen is confined in the small space between two helical coils. In these calculations, the inconsistency of the density profile of molecular hydrogen between at toroidal angles of ϕ = 0 and 34 deg. (nearly one toroidal pitch angle) is observable. Specifically, the high density region is located in the upper outer and the lower outer side for ϕ = 0 and 34 deg., respectively, which clearly shows the toroidal discontinuity of the neutral density profile. This is caused by the three-dimensionally complicated distribution of the neutral release rate from the divertor plates near the mirror walls (both toroidal ends), and by the complicated shape of the LHD vacuum vessel and plasma.

Figure 3 gives the five toroidal cross sections of the density profiles of neutral hydrogen molecules in the grid model with the warp walls. Hydrogen molecules are localized in the inner region as well as these in the model with mirror walls. The density profiles near the both toroidal ends (at ϕ = 0 and 34 deg.) are fairly consistent, showing no observable toroidal discontinuity. These calculations indicate that the new warp walls can be successfully applied to the detailed simulation of neutral particle transport in the three-dimensionally complicated geometry such as LHD.

4. Analyses of neutral particle transport in a closed divertor configuration

For a preliminary study of the closed divertor configuration in LHD, we constructed a three-dimensional grid model with the warp walls including baffle plates which are fully helically installed along the space between the two helical coils. The distance between an X-point of the plasma and the head of the baffle plates is set to be 150 mm (the gap between the two baffles is about 300 mm). Figure 4 illustrates the five toroidal cross sections of the density profile of neutral hydrogen molecules. The distribution and quantity of the release rate of hydrogen molecules from the divertor plates are identical with these in the model without the baffle plate (Figs. 2 and 3). The neutral density between two helical coils is higher than that without the baffle plates, which indicates the effective confinement of neutrals in the divertor region due to suppression of the outflow of neutral particles from the divertor plates to the main plasma region. The figure shows that the baffle plates significantly increase molecular hydrogen density in inner divertor region. The insets in Figs.

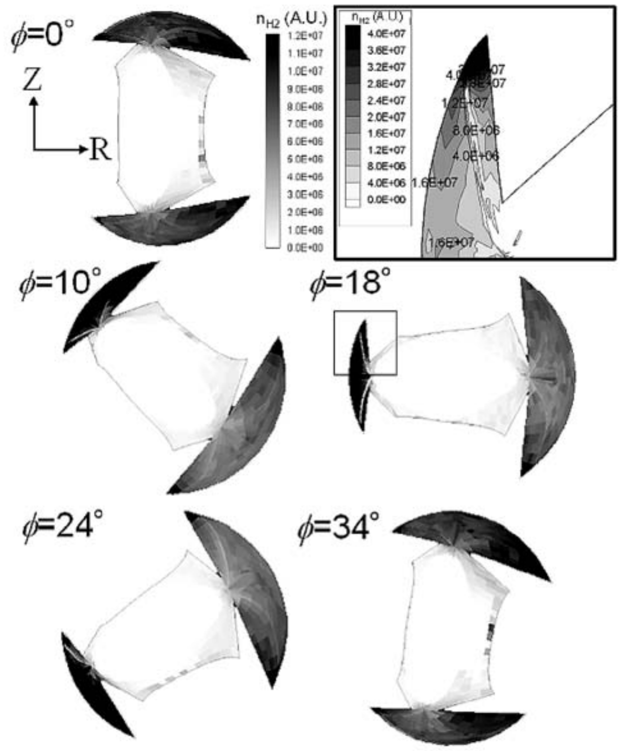

Fig. 4 Five toroidal cross sections of the profiles of neutral hydrogen molecules in the grid model including a fully helically baffle plates with the warp walls. Upper right illustration shows the enlarged contour plot of the density profile in inner divertor region.

3 and 4 are the enlarged contour plots of the density profile of molecular hydrogen in inner region, showing that the density of molecular hydrogen around a divertor leg in the case without and with the baffle plates ranges from 4.0×10^6 to 8.0×10^6, and from 4.0×10^6 to 1.6×10^6 (A.U.), respectively. It indicates that the molecular hydrogen density in this region with the baffle plates increases about twice as much as that without the baffle plates, which is favorable for achieving divertor detachment and efficient particle control in the LHD plasma periphery.

Fully helical installation of the baffle plates is actually impossible because the accessibility from vacuum ports to the main plasma is indispensable for plasma heating and diagnostic systems. The calculation in Fig. 4 strongly suggests that the cost-effective particle removal and control can be realized by installing the baffle plates only in inner divertor region because of effective confinement of the high density neutral hydrogen molecules in this region. It can almost keep accessibility to the main plasma from vacuum ports (except for from inner ports). Measurements of a fast ion gauge suggest that the vacuum pressure in the present LHD divertor region is about one-order of magnitude lower than that in Tokamak open divertor cases [13]. That is, the present vacuum pressure in the LHD divertor is not enough for achieving divertor detachment. An optimized closed divertor configuration is a possible candidate to achieve divertor detachment in LHD plasmas, because actual neutral density in the divertor region can be further increased by the enhanced release rate of neutral hydrogen molecules on the divertor plates due to the plasma flow on the divertor leg produced by the ionization of recycled hydrogen from the divertor plates. For quantitative prediction of the vacuum pressure in the divertor region, detailed analyses of neutral particle transport coupling with a fully three-dimensional plasma transport simulation will be necessary in the future.

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