Neutral Particle Transport Simulation around a V-Shaped Target Using DEGAS 2 Code*)

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A method proposed most recently for heat flux reduction in a divertor is to use a so-called V-shaped target plate. A numerical study of neutral behavior around the V-shaped target in the divertor simulator, Test Plasma produced by Directed current device for sheet plasma (TPD-SheetIV), using DEGAS 2 is reported. The neutral distribution and H-alpha emission profile are modeled and compared for three types of targets, mainly for the low-density attached condition. Under this condition, excited atoms are produced by electron impact with recycled atoms near the target, and hence, H-alpha emission has a peak there.

Keywords: TPD-SheetIV, V-shaped target, detached plasma, DEGAS 2, gas puffing

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1. Introduction

In fusion reactors such as the International Tokamak Experimental Reactor (ITER), tremendous heat flux (> 10 MW/m^2) is expected to flow onto divertor target plates. The development of for reducing the heat flux on the divertor plate is an important challenge for the future fusion reactor design. One of the most promising methods is to establish a so-called detached plasma, whose electron temperature is kept below 1 eV by powerful cooling due to gas puffing. The most recent proposal is to use a so-called V-shaped target plate, which is expected to increase the local neutral density and enhance the volume recombination process [1].

Experimental simulation of a V-shaped target via detached hydrogen plasma formation in the linear divertor plasma simulator, Test Plasma produced by Directed current device for sheet plasma (TPD-SheetIV), has been conducted [2, 3]. The V-shaped target enhances recycling, and plasma detachment is effectively achieved in that device. Under such conditions, neutral particles are expected to experience not only transport but also atomic/molecular processes such as dissociation and ionization. Their behavior has been experimentally studied mainly with H-alpha monitors. However, because of a limited number of ports and channels in the experimental devices, an iterative simulation to determine such parameters is indispensable.

In this paper, the preliminary mesh model for the TPD-SheetIV experiment described in [4] is improved and broadened to include three types of targets. As a first step, the plasma parameters used here are one-dimensional, which is similar to the attached condition. In section 2, we briefly explain the TPD-SheetIV device and its operation in simulating detached plasma. A two-dimensional (2D) model geometry is constructed for comparison with experimental results. In section 3, we explain DEGAS 2 code used in this work and the simulation model we developed. In sections 4 and 5, the obtained neutral hydrogen distributions and H-alpha emission profiles, respectively, are shown. Section 6 presents the conclusion.

2. TPD-SheetIV Device

TPD-SheetIV consists of the plasma source and divertor experimental regions [5]. A steady state plasma is produced by a TPD-type dc discharge, which passes through the anode slit and forms a sheet shape. Neutral pressure in the experimental region is controlled with the gas puff intensity at the chamber wall. Normal direction (x) profiles of plasma sheet parameters such as the electron density and the electron temperature are provided by a plane Langmuir probe. The power on the target is measured by a calorimeter. Hydrogen Balmer spectra have been measured in a detached hydrogen plasma with hydrogen gas puffing.

Three types of target geometry (V-shaped, oblique, and vertical targets) have been examined. A detached condition with high radiation loss is easily produced at the V-shaped target [2, 3].

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3. DEGAS 2 Code and Simulation Model

The DEGAS 2 neutral transport simulation code [6] is the successor to the DEGAS code [7]. DEGAS has already been applied to complicated edge geometries such as those in helical systems, and this provieded us with neutral particle information [8]. However, constructing the simulation mesh model for DEGAS is rather difficult and requires considerable time and effort. Moreover, Cartesian coordinate can not be used to properly describe a sheet plasma in DEGAS modeling. In contrast, DEGAS 2 has a new mesh generator utility that makes it easier to modify the target geometry and compare the results of different geometries. In this work, the preliminary mesh model for the TPD-SheetIV experiment described in [4] is improved and three mesh models for V-shaped, oblique, and vertical targets are constructed.

Figure 1 shows the simulation model of the vertical target. The experimental region of TPD-SheetIV is modeled by a rectangular parallelopiped with a width (x direction) of 0.15 m and a length (z direction) of 0.18 m, which are divided into 70 meshes (x) and 60 meshes (z), respectively. Because the height of the plasma sheet is very small (3 ∼ 10 mm), the mesh separation is reduced near target ($x \sim 7.5$ cm, $z = 0$). Homogeneity in the y direction is assumed. The other target models are similar to Fig. 1. The "definegeometry2d" module of DEGAS 2 uses Jonathan Shewchuk's Triangle package and can produce triangle zones smoothly.

The particle sinks are a plasma inlet from the source region and three pumping ducts. If test particles reach these sinks, they are considered to be lost from the system. On the other hand, if test particles reach the wall, they are reflected according to wall reflection data. Because the plasma density is not very large, the loss of test particles in the plasma is negligibly small. Three types of particle sources are considered: recycling at the target plate, volume recombination in the chamber, and gas puffing at the left wall gas feeder, and their contributions are compared.

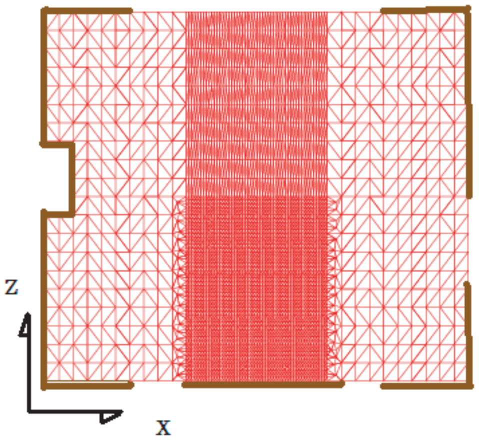

Fig. 1 Schematic view of the model geometry of TPD-SheetIV target chamber. Left bottom corner is the origin. Plasma inlet from the source chamber is at $z = 0.18$ cm. Gas puff feeder is at the left chamber wall ($x = 0$ m). One port exists in the right wall.

4. Neutral Particle Distribution

Figure 2 shows the hydrogen molecular pressure obtained for total gas puff intensity of $4.0 \times 10^{20}\,\mathrm{s^{-1}}$. The plasma parameters are obtained from the $P_{\mathrm{DIV}} = 0.8$ mtorr case in [5]. Thus the recycling source intensity is of the same order as the puffs, and the recombination source contribution is negligibly small. Although the simulation geometry is divided into two regions by the sheet plasma at $x \sim 7.5$ cm, neutral particles emitted from the gas feeder at the left-center wall can easily reach the region in the right and the ionization loss in the plasma sheet is very small. Therefore, even a 2D model that extends only 4 ∼ 5 cm in the y direction without sheet plasma edge could at least qualitatively predict the neutral particle behavior. The obtained neutral pressure seems to be slightly lower than 0.8 mtorr, and hence, further improvement of the mesh geometry is necessary.

Figure 3 shows the hydrogen molecular pressure obtained for the V-shaped target. Although the plasma data in [5] are obtained from a vertical target experiment, they are also used in this simulation. Because the contribution of recycled particles at the target is not very large in the neutral particle balance, this is not an inaccurate assumption. In this case, the neutral pressure near the gas feeder is higher than that in Fig. 2. The movement of neutrals toward the two duct ports located on the right side of the geometry is hindered by the V-shaped target plate. Thus, the precise modeling of the target's shape is important.

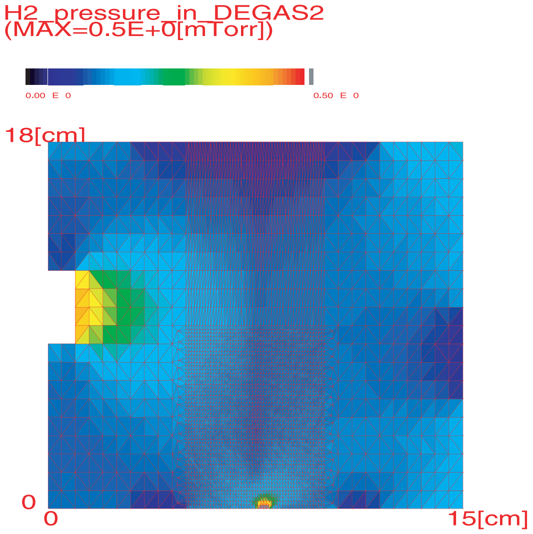

Fig. 2 Neutral pressure distribution for vertical target. Geometry is the same as in Fig. 1, and plasma parameters are those for the attached condition. Intensity of gas puff source is $4.0 \times 10^{20}\,\mathrm{s^{-1}}$.

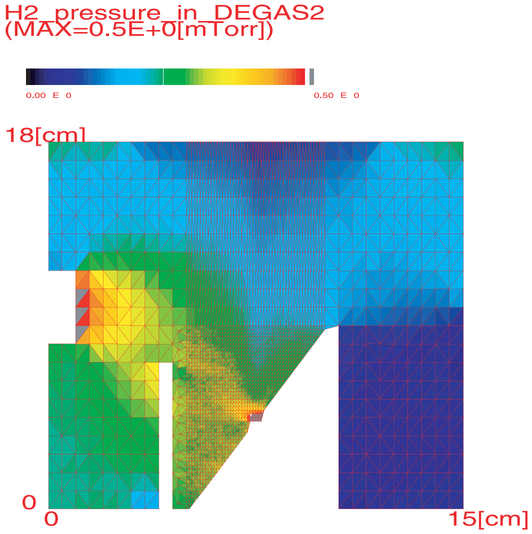

Fig. 3 Neutral pressure distribution for V-shaped target. Plasma parameters and gas puff source intensity are the same as in Fig. 2.

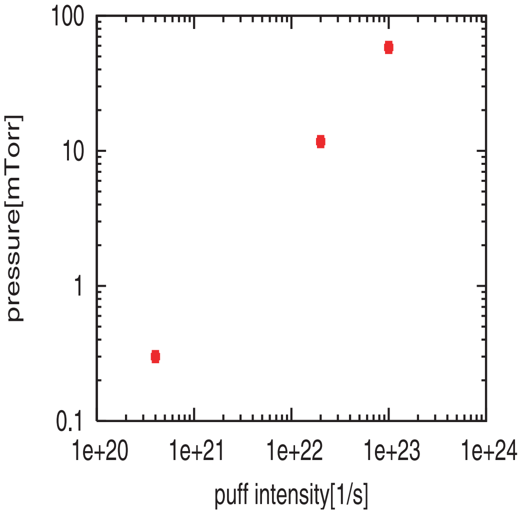

Fig. 4 Neutral molecular pressure sampled around $x = 1.5$ cm and $z = 7.5$ cm versus the intensity of gas puff neutral sources.

Figure 4 shows the approximately linear relationship between the gas puff source intensity and the neutral pressure sampled around $x = 1.5$ cm and $z = 7.5$ cm, where a pressure gauge is located. Because the profiles of the plasma parameters in the detached condition differ from those in the attached condition, they should be adjusted for each run. However, as a first trial to observe the approximate relationship, the plasma parameters used in Fig. 2 were applied for all runs. The experimental plasma in TPD-SheetIV shows an increase in electron density and a decrease in target heat load at approximately 5 mtorr. Therefore, simulation at higher pressures should be repeated with the detached plasma parameters.

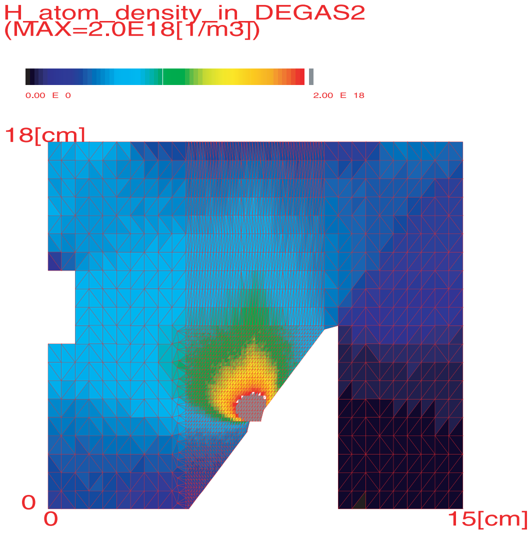

Fig. 5 Hydrogen atom density distribution for inclined target. Plasma parameters and gas puff source intensity are the same as in Fig. 2.

Figure 5 shows the hydrogen atom density obtained for the conditions in Fig. 2. Hydrogen atoms are mainly generated at the ion reflection point on the target plate. Dissociation of hydrogen molecules reaching the plasma sheet is also observed, but at this low pressure condition, its contribution is very small. The inclined target guides atoms toward the left.

5. H-alpha Emission Profiles

H-alpha line results from the radiative decay of excited hydrogen atoms from the principle quantum state $n = 3$ to $n = 2$: it is widely used to monitor neutral hydrogen behavior. The line intensity is a measure of the density of H($n = 3$), and its wavelength spectrum reflects the velocity distribution of hydrogen atoms. As many pathways are available for generating H($n = 3$), several of its groups exist with different densities and characteristic energies. Therefore, the shape of the hydrogen Balmer spectrum depends upon complex atomic/molecular processes including excited states. To determine the most important process, the calculated spectra must be compared with the observations. However, in this work, the number of test flights is only 10^5, and the statistical error for spectral calculation is still large.

Figure 6 shows the H-alpha emission intensity obtained for the condition in Fig. 2. Because electrons exist only in the sheet plasma, the emission profile is localized around it. Along the z direction, the emission intensity is highest at the target plate. Thus H($n = 3$) is expected to be produced by electron impact excitation of ground state hydrogen atoms, which also have a density peak there like as shown in Fig. 5.

Figure 7 shows the H-alpha emission intensity at a higher pressure. The plasma parameters are the same as in Fig. 2, but the gas puff source intensity is 1.0×10^{23} s^{-1}.

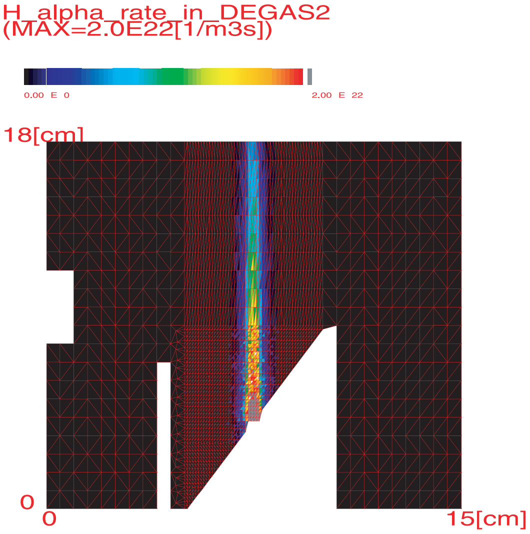

Fig. 6 H alpha emission distribution for V-shaped target. Plasma parameters and gas puff source intensity are the same as in Fig. 2.

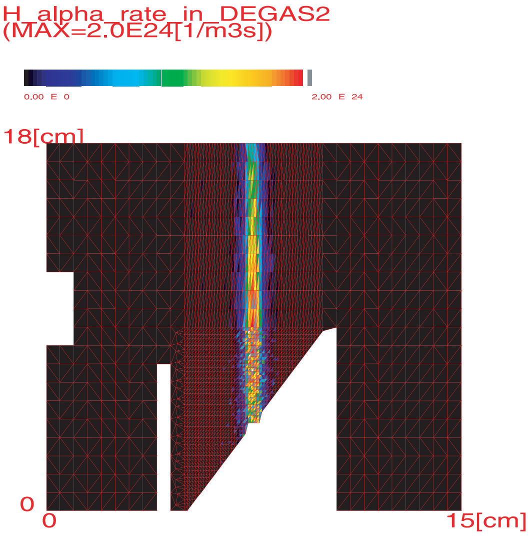

Fig. 7 H-alpha emission distribution for V-shaped target. Plasma parameters are the same as in Fig. 2, but gas puff source intensity is 1.0×10^{23} s^{-1}.

In this case, a large number of hydrogen molecules puffed from the gas feeder dissociate around the plasma sheet, and the atomic density peak moves away from the target plate. H(n = 3) is also directly produced by molecular dissociation, and hence, H-alpha emission is greatest at the center of the simulation geometry.

For the line-integrated emission and spectral shape, we must carefully consider the properties of the spectrometer used in the experiment. The statistical accuracy must also be improved using more test flights.

6. Conclusion

A 2D mesh model geometry for three types of target plates in the divertor simulator TPD-SheetIV were constructed to study neutral particle behavior. The results of this study are as follows.

- Attenuation of puffed molecules in a sheet plasma is not significant. At least as a first estimate, the effect of the finite width of the sheet plasma might be ignored, although a three-dimensional simulation to verify this might be conducted in the future.
- The hydrogen molecular density is dominated by neutral source input from gas puffs. Recycling at the target plate has only a minor effect.
- The neutral source of recycling at an inclined target shows some errors, but they can be avoided, and the relationship between the molecular pressure and the neutral source is verified.
- At low pressure, hydrogen atom production occurs at the target's surface. If the pressure increases, molecular dissociation becomes dominant, and the H-alpha emission peak also moves along the plasma sheet.

Our simulation has still not yielded the exact experimentally observed pressure value. This implies that the mesh model needs to be improved, such as changing in the port size and pumping effect, which will be performed in a future study. For a more accurate comparison with experimental results, an improved calculation of H-alpha spectra will also be necessary.

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