ELSEVIER

Journal of Nuclear Materials 220–222 (1995) 1001–1004

journal of nuclear materials

Monte Carlo simulation on active helium-ash exhaust by divertor biasing

Tatsuya Kuwabara [a], Masahiro Kojima [a], Noriyasu Ohno [b], Yoshihiko Uesugi [b], Shuichi Takamura [b], Yasunori Yamamura [c]

[a] *Dept. of Electrical Engineering and Electronics, School of Engineering, Nagoya University, Nagoya 464-01, Japan*
[b] *Dept. of Energy Engineering, School of Engineering, Nagoya University, Nagoya 464-01, Japan*
[c] *Okayama University of Science, Ridai-cho, Okayama 700, Japan*

Abstract

An effective helium-ash exhaust from the tokamak edge region using reduced helium recycling by divertor plate biasing is numerically studied. The amount of the passing neutral particles is calculated taking into account the reflection on the divertor plate and the recycling process of the reflected neutrals between the divertor and the SOL plasma. The ion incident energy is determined by the sheath voltage, which is controlled by the divertor biasing. Numerical studies show that the optimum structure of the divertor plate and the pump ducts, and the control of the ion energy imply a possibility of selective helium-ash exhaust. In this calculation we obtain an enhancement factor of about 3 for the ratio of helium to deuterium incident on the divertor plate.

1. Introduction

Helium-ash exhaust is one of the most crucial problems for the steady state operation in the thermonuclear reactor. It is necessary to keep the helium concentration in the core region below 10% for high fusion reactivity. The control of the plasma flow with divertor biasing has been studied on TdeV [1] and the helium or deuterium separation from the pumped gas is suggested by using a deposited nickel surface [2] or a niobium membrane [3]. The optimum divertor and pump duct geometry has been studied using DEGAS and B2 codes [4].

In this study, a selective helium-ash exhaust from the divertor plasma region through reduced helium-recycling by divertor plate biasing is studied numerically. The incident energy of ions is determined by the sheath voltage of the divertor plate, which is controlled by the divertor biasing. Some of the fast neutrals reflected from the divertor plate pass through the SOL plasma. The slower neutrals are easily ionized in the SOL, and recycle between the divertor plate and the SOL plasma. The energy and angular distributions of reflected particles are calculated by the "ACAT code" [5]. The amount of the passing neutral particles is calculated taking into account the reflection from the divertor plate and the recycling process of the reflected neutrals between the divertor and the SOL plasma. The preliminary results show that the preferential pumping of helium is determined mainly by the difference of ionization mean free path between helium and deuterium, and has a weak dependence on the biasing voltage.

2. Concept of helium-ash pumping by divertor biasing

The helium-ash that is left behind after D–T thermonuclear reaction diffuses across the separatrix and flows onto the divertor along the magnetic field line through the SOL plasma. Incident ions to the divertor plate are backscattered to the divertor plasma mainly as neutral particles. Reflected neutral particles are either ionized in the divertor plasma or pass through it. Some of the passing neutral particles are reflected back into the SOL plasma by the wall. When the energy of incident particles are controlled by the divertor biasing, the energy of the neutral particles reflected from the divertor plate can be changed and its mean

SSDI 0022-3115(94)00461-7

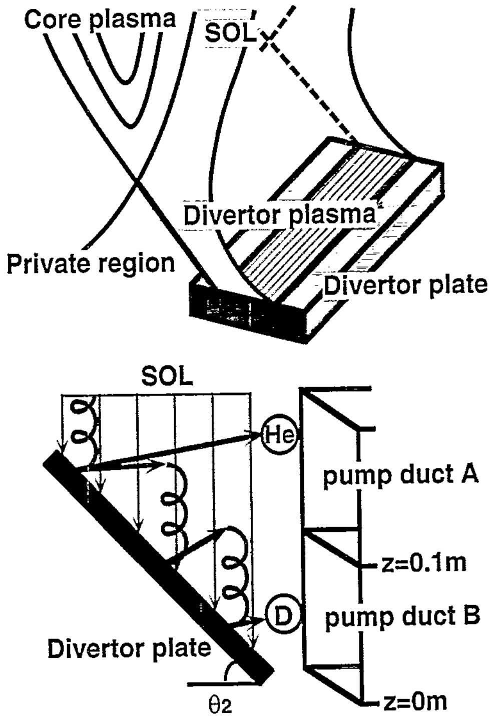

Fig. 1. Configuration of the selective helium-ash pumping by divertor biasing.

free path of the ionization on the electron-impact is varied. We assume that the bias voltage is applied to a part of the divertor plate in front of the pump duct and the divertor biasing does not change the plasma potential. The sheath potential is fixed to bias voltage. Ion acceleration energy is the sheath potential. The mean free path of the energetic neutral particle is longer than that of the slower particles, the energetic neutrals reach the pump ducts without being ionized and the slower neutrals are easily ionized in the divertor plasma. For the selective helium-ash removal it is required that the ionization mean free path of helium is longer than the thickness of the SOL and that of deuterium or tritium is shorter. A schematic configuration of helium pumping by divertor biasing is shown in Fig. 1. The ionization mean free path by electron impact as a function of the neutral energy is shown in Fig. 2, taking the electron temperature as a parameter. For higher electron temperature, the difference between the ionization mean free path of helium and that of deuterium is negligible.

3. Monte Carlo simulation and results

It is important to study the recycling process of helium and deuterium in the divertor plasma. We evaluate the helium and deuterium particle transport. The trajectory of helium and deuterium ions in the divertor region is studied using the Monte Carlo particle simulation code. The elastic collision with a neutral particle, ionization by electron impact, charge transfer between deuterium neutral and deuterium ion, the friction due to the plasma flow, Coulomb force, electric force and reflection from the divertor plate are considered. The charge transfer between helium atom and deuterium ion is neglected. It does not have any effects on the results because its cross section is smaller than the ionization cross section of helium for electron impact. These data are taken from Ref. [6]. The re-emission of the trapped particles from the divertor plate and the sputter from the divertor plate are not taken into account in the present calculation. A slab model is shown in Fig. 3. Its thickness d is 0.1 m. The separatrix is in the plane of $y = 0.1$ m. The distributions of the electron temperature and density are defined as follows:

$$T_e(y) = T_e^{sep} \exp\left(-\frac{d-y}{d}\right), \tag{1}$$

$$n_e(y) = n_e^{sep} \exp\left(-\frac{d-y}{d}\right). \tag{2}$$

The electron temperature on the separatrix is T_e^{sep}, the

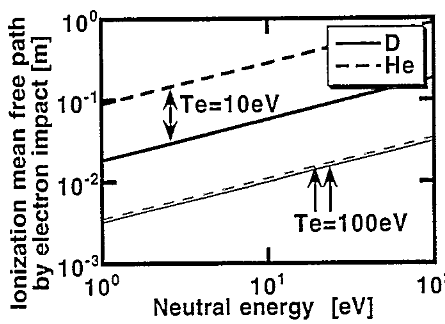

Fig. 2. The ionization mean free path by electron impact as a function of the neutral energy, taking the electron temperature as a parameter.

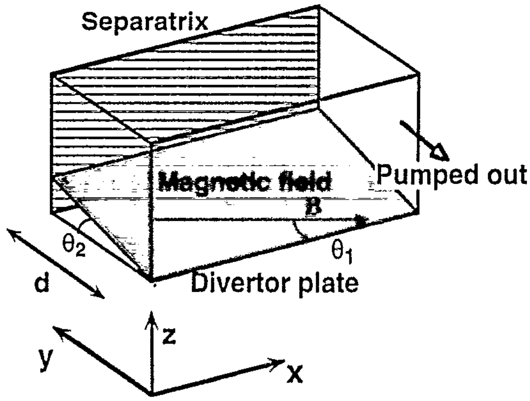

Fig. 3. Model configuration of the Monte Carlo code.

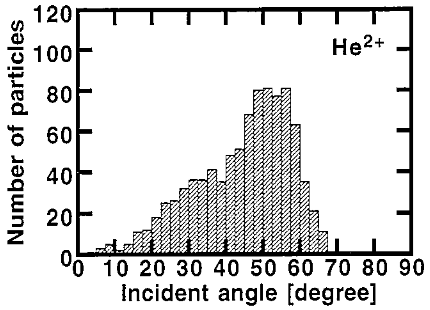

Fig. 4. The distribution of the incident particles on the divertor plate. $T_e = 10$ eV, $n_e = 1.0 \times 10^{20}$ m^{-3}, $T_i = 10$ eV, $B = 1.0$ T, the angle between the magnetic force line and the normal line of divertor plate = 88°, the ion acceleration energy = 10 eV.

electron density is n_e^{sep} and d is a decay length of the SOL. T_e^{sep} is 10 eV and n_e^{sep} is 1.0×10^{20} m^{-3}. The decay lengths of the electron temperature and electron density in the direction of y are 0.1 m. The ratio of the mean free path of helium to that of deuterium is about 5 in this plasma parameter. Helium ions are assumed to be doubly charged. The profiles of the plasma potential, flow velocity, electron density in the pre-sheath region along the magnetic field line in the divertor plasma are solved from the one-dimensional fluid equations for the deuterium plasma. The ion acceleration energy including a sheath voltage is controlled by the bias voltage. A cyclotron gyration of the test particle is considered in the pre-sheath region. When the test particles strike the divertor plate in an oblique magnetic field, the ions hit against the wall with an angular distribution shown in Fig. 4. The angle of 0° indicates the normal incidence. Angular and energy distributions of the reflected particle on the surface of the divertor plate are calculated with ACAT code taking into account the oblique incidence of ions. The divertor plate material is tungsten. Reflected particles are traced again in the divertor plasma. The distributions of an "escape time" and a "height" are shown in Fig. 5. The escape time is referred to the existent time in the plasma and the term "height" indicates the distance of the pumped particle from the divertor plate on the plane $y = 0$, namely z. The helium particle escapes from the plasma faster than deuterium since the helium passes through the plasma with almost single reflection on the divertor plate and the deuterium is easily ionized and recycles in the divertor. The height distribution of passing helium particles also differs from that of deuterium. The passing deuterium particles are localized around the bottom of the pump duct but helium travels to a higher vertical position. If we assume that the pump duct is separated into two parts, most of the deuterium particles enter the bottom pump duct, while the helium particles go into the top pump duct.

We define the helium-ash pumping enhancement

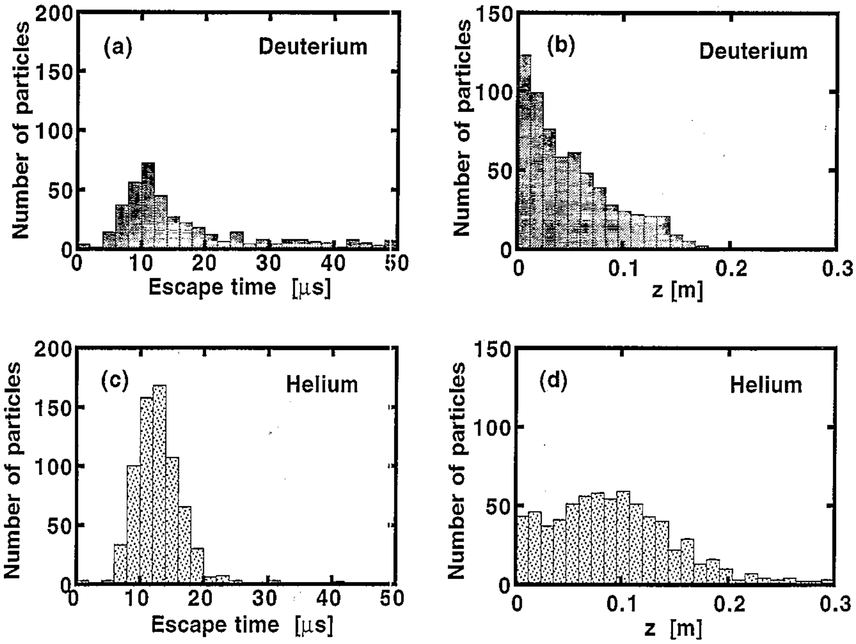

Fig. 5. The distribution of the escape time and the height of the exhausted particle. $T_e^{sep} = 10$ eV, $n_e^{sep} = 1.0 \times 10^{20}$ m^{-3}, $T_i = 10$ eV, $\theta_1 = 2°$, $\theta_2 = 70°$, $B = 1.0$ T, the ion acceleration energy = 10 V.

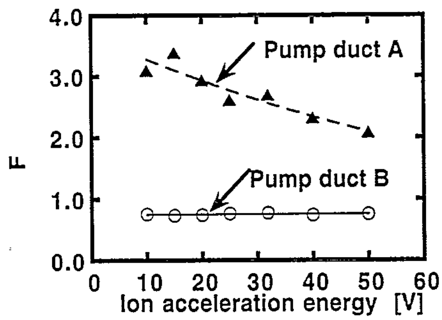

Fig. 6. The helium-ash pumping enhancement factor F in the top pump duct A and that of the bottom pump duct B as a function of the ion acceleration energy. The same plasma parameters as in Fig. 5 are used.

factor F to evaluate the preferential helium pumping. This factor, F, is defined as follows [4]:

$$F = \frac{n_{\mathrm{He}}^{\mathrm{pump}}/n_{\mathrm{He}}^{\mathrm{div}}}{n_{\mathrm{D/T}}^{\mathrm{pump}}/n_{\mathrm{D/T}}^{\mathrm{div}}}, \tag{3}$$

n^{pump} is the number of particles going out to the pump duct and n^{div} is the number of ions striking the divertor plate. In this calculation n^{div} is fixed to 1000. After this, the value of F in the pump duct A will be compared with that of the pump duct B.

The enhancement factor F in the pump duct A and B as a function of the ion acceleration energy is shown in Fig. 6. When the bias voltage higher than the floating potential (~ 30 eV) is applied, the number of exhausted helium particle is about 3 times larger than that of deuterium in the pump duct A and the value of F is less than 1 in the pump duct B. When the bias voltage lower than the floating potential is applied, both deuterium and helium particles reach the pump ducts as neutral particles. Therefore the enhancement factor F in the pump duct A and B get close to unity. Particle reflection coefficient R_{N} and energy reflection coefficient R_{E} are almost independent on the incident energy in this range [7]. The incident energy of the full ionized helium is larger than that of deuterium. Fraction of the particles across the separatrix as a function of the angle of the divertor plate θ_2 is shown in Fig. 7. The number of particles that return to the core plasma or private region plasma across the separatrix decreases with increasing the angle θ_2. Most of the backscattered particles do not return to the core plasma or private region when the angle of divertor plate θ_2 is larger than 70°.

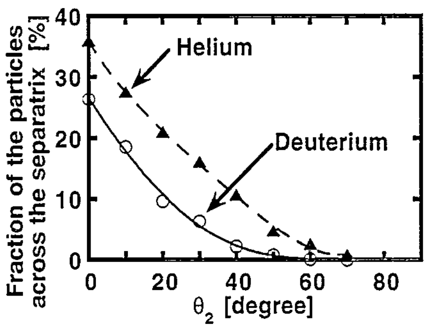

Fig. 7. Fraction of the particles across the separatrix as a function of the angle of the divertor plate. The same plasma parameters as in Fig. 5 are used.

4. Conclusion

The preferential pumping of helium-ash can be achieved by the control of incident ion energy into the divertor plate by divertor biasing and the optimization of the divertor plate and pumping duct configurations. The number of the exhausted helium particle is about 3 times larger than that of deuterium in the top pump duct when the bias voltage higher than the floating potential is applied. The number of particles that return to the core plasma or private region across the separatrix decreases with increasing the angle between the divertor plate and the horizontal plane. Most of the backscattered particles do not return to the core plasma or private region when the angle of the divertor plate θ_2 is larger than 70°. In this study we cannot obtain the self-consistent solution of the helium and deuterium transport because we use the single particle simulation code.

Acknowledgements

One of the authors (T.K.) would like to thank Dr. S. Sakurai (JAERI), Dr. S. Sasaki (Toshiba) and Dr. K. Shiraishi (Hitachi) for valuable discussions. This work was supported by the Japan Ministry of Education, Science and Culture through a grant-in aid for scientific research (contract no. 05452393).

References

[1] R. Décoste et al., Proc. 20th EPS Conf. on Controlled Fusion and Plasma Physics, Lisboa, Portugal, 1993, vol. 17C, part I, p. I-295.
[2] A.I. Livshits et al., J. Nucl. Mater. 196–198 (1992) 159.
[3] A.Yu. Pigarov et al., J. Nucl. Mater. 196–198 (1992) 1121.
[4] D.N. Ruzic et al., J. Nucl. Mater. 176/177 (1990) 926.
[5] W. Takeuchi and Y. Yamamura, Radiat. Eff. 71 (1983) 53.
[6] R.A. Phaneuf, Atomic and Plasma–Material Interaction Data for Fusion, vol. 2 (1992) 75.
[7] W. Eckstein et al., Appl. Phys. A 38 (1985) 123.