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Numerical Analysis of Impurity Transport Along Magnetic Field Lines in Tokamak Scrape-Off Layer

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Abstract

Transport of carbon and boron impurity ions parallel to magnetic field lines in the tokamak SOL (scrape-off layer) is numerically investigated for a one-dimensional steady state. The spatial distributions of density and velocity of the impurity ions in a steady state are calculated by finite difference method for a single-fluid model. The calculated results show that among forces acting on SOL particles thermal force produced by plasma temperature gradient is a principal force determining the feature of impurity distribution profiles in the tokamak edge. However, strong collisional friction forces appearing dominant in front of the divertor plate restrain impurity ion flows due to temperature gradients from moving toward the midplane. Consequently, the stagnation point develops in the impurity flow by these two forces near the divertor region, in which ion flows change their directions. Impurity ions turn out to be accumulated at the stagnation points, where peaked profiles of highly-ionized state ions are relatively predominant over those of low-ionized state ions.

1. Introduction

The impurity transports in tokamak SOL(Scrape-Off Layer) are important issues regarding to PFC(Plasma Facing Component) design for impurity control in tokamak plasmas[1-6]. PFC' s, such as first wall, limiter, and divertor, are the origins of impurity production resulted from striking of energetic particles from the core plasma on the material surface. Recycling neutral atoms produced by plasma-surface interactions are impurity ion sources in the tokamak SOL established by limiter and/or divertor configurations in the tokamak edge region to inhibit impurities from penetrating into the core plasma. Divertor configuration is a more promising control scheme for impurities than limiter one. Impurity ions in the SOL transport mainly in the parallel direction along magnetic field lines because their cross-field motions due to grad-B and curvature drifts and collisional diffusions can be neglected compared with their guiding center motions along field lines owing to electrostatic, temperature gradient, and collisional friction forces. Background plasmas in the SOL generate various forces exerting on impurity ions due to temperature gradients, electric fields and collisional frictions, and these forces determine the

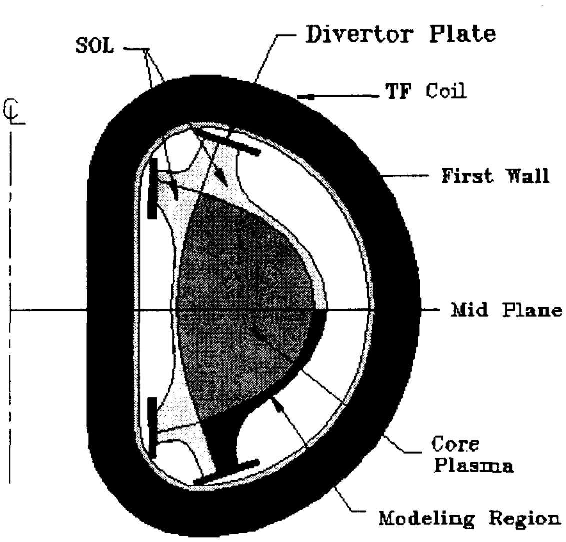

Fig. 1. Schematic of Tokamak Cross Section with a Double-Null Configuration

transport behavior of impurity ions in the diverted tokamak edge region.

In this study, a one-dimensional numerical analysis of impurity ion transport parallel to magnetic field lines is performed in a diverted tokamak edge region with double-null configuration as shown in Fig.1. Finite difference method is employed as a numerical scheme solving the continuity and momentum equations of a single-fluid model. The SOL background plasma values such as density, temperature, velocity and electric field are provided by the two-dimensional edge plasma transport code, EDGETRAN[2,7]. Steady-state distributions of carbon and boron impurity neutrals originated from the first wall and divertor plates are prescribed respectively for the calculations. Distributions of density and flow velocity for carbon and boron ions in their charged states from singly to fully ionized states are calculated by the developed one-dimensional code along magnetic field lines from midplane to divertor plate.

This one-dimensional modeling provides a qualitative understanding of impurity ion transports parallel to magnetic field lines under the background plasma influence. From the calculated impurity field distributions of carbon and boron, a dominant force producing resultant profiles along the magnetic field line is found, and the role of each force and the feature of impurity ion transports are discussed.

2. Governing Equations

The distributions of impurity density and velocity profiles in a steady state are found from continuity and momentum equations in a one-dimensional fluid model, where the direction of flow along the magnetic field is projected on the x coordinate. The following conservation equations are solved for each impurity ion in a charged state of z :

$$\frac{\partial}{\partial x}(n_z v_z) = I_{z-1} n_{z-1} - (I_z + R_z) n_z + R_{z+1} n_{z+1} \tag{1}$$

$$\begin{aligned} \rho_z v_z \frac{\partial v_z}{\partial x} + \frac{\partial p_z}{\partial x} - n_z ZeE - \rho_z \frac{v - v_z}{\tau_z} \\ - \alpha_z n_z \frac{\partial T_e}{\partial x} - \beta_z n_z \frac{\partial T_i}{\partial x} \\ = I_{z-1}\rho_{z-1} v_{z-1} + R_{z+1}\rho_{z+1} v_{z+1} \\ - (I_{z-1}\rho_{z-1} + R_{z+1}\rho_{z+1}) v_z \end{aligned} \tag{2}$$

where

ρ_z : impurity mass density (m_z n_z)
I_z : ionization rate($<\sigma v_e>_i n_e$)
R_z : recombination rate($<\sigma v_e>_r n_e$)
τ_z : Spitzer slowing down time [8]
α_z : thermal force coefficient for electron [9]
β_z : thermal force coefficient for ion [10]

The impurity density n_z is calculated in the continuity equation (1), in which ionization from the (z-1)th and recombination from the (z+1)th contribute as sources while ionization to the (z+1)th and recombination to the (z-1)th reduce particle numbers of the z-th charged state as sinks. The impurity flow velocity v_z is determined from the momentum equation (2), where the pressure p_z is calculated as a product of density and temperature, $n_z kT_i$, with an assumption of $T_z \simeq T_i$ for simplicity. This assumption can be justified with the fact that T_z is included only in the pressure gradient term which is generally small.

The electric field E providing the charge neutrality in plasma ($n_e \simeq z n_i$) is found from the parallel component of electron momentum equation and obtained as the following :

$$E = -\frac{1}{n_e e}\left(\frac{\partial p_e}{\partial x} + 0.71 n_e \frac{\partial T_e}{\partial x}\right) \quad (3)$$

where e is the electron charge, k is the Boltzmann constant, and T_e is the electron temperature in eV. In addition, the background edge plasma fields, such as electron density n_e, temperatures T_e and T_i, and plasma velocity $\boldsymbol{v}$ in Eqs. (1) ~ (3), are found from a set of plasma transport equations[2,7] based on the Braginskii's two-fluid equations describing particle, momentum, and energy conservations for electrons and ions in the tokamak SOL.

The thermal forces are produced by electron and ion temperature gradients. These forces arise in the form of the fifth and sixth terms in the left hand side of Eq. (2). The momentum transfer by a collision between plasma and impurity ion, the fourth term in the left side of Eq.(2), derives impurity ions into flowing toward the divertor plate. When the plasma velocity is not so high enough to overcome the thermal force, the net flow of ions could develop toward midplane region.

3. Differencing Schemes for Governing Equations

3.1. Continuity Equation

A forward differencing scheme is used in the numerical simulation for the fluid flux term in the continuity equation. To avoid the enlargement of negative density, the continuity equation is descretized as follows by considering particle losses and gains balanced at a grid point in the steady state :

$$\pm\frac{(n_z v_z)_i}{dx_i} + (I_z + R_z) n_{zi} = \begin{cases} \dfrac{(n_z v_z)_{i-1}}{dx_i} + I_{z-1} n_{z-1} + R_{z+1} n_{z+1} & (v_{z(i-1)} > 0) \\ -\dfrac{(n_z v_z)_{i+1}}{dx_i} + I_{z-1} n_{z-1} + R_{z+1} n_{z+1} & (v_{z(i+1)} < 0) \end{cases} \quad (4)$$

where $dx_i = x_i - x_{i-1}$

3.2. Momentum Equation

For the numerical treatment of convection terms, one should employ an upwind differencing scheme instead of a central differencing method. The following approximation is applied to the convective term, $v_z \dfrac{\partial v_z}{\partial x}$ in the momentum equation:

$$v_z \frac{\partial v_z}{\partial x}\bigg|_i = \begin{cases} v_{zi}^* \dfrac{v_{zi} - v_{z(i-1)}}{dx_i} & (v_{zi}^* > 0) \\ v_{zi}^* \dfrac{v_{z(i+1)} - v_{zi}}{dx_{(i+1)}} & (v_{zi}^* < 0) \end{cases} \quad (5)$$

where v_{zi}^* is a value calculated at the previous iteration step. The central differencing scheme is used on the other derivative terms such as $\dfrac{\partial p_z}{\partial x}$, $\dfrac{\partial (kT_e)}{\partial x}$, and $\dfrac{\partial (kT_i)}{\partial x}$, i.e.,

$$\left.\frac{\partial f}{\partial x}\right|_i = \frac{f_{i+1}-f_{i-1}}{dx_i + dx_{i+1}} \qquad (6)$$

where $dx_{i+1} = x_{i+1} - x_i$. The central differencing scheme yields a tri-diagonal matrix, to which LU decomposition method[11] is applied to solve the matrix.

3.3. Boundary Conditions

In view of a symmetric configuration about the midplane of SOL, Neumann condition is implemented as a boundary condition at the midplane (x=0) for the calculation of impurity density in Eq.(1).

$$\left.\frac{\partial n}{\partial x}\right|_{x=0} \quad x = 0 \qquad (7)$$

Dirichlet condition for impurity flow velocity is given as a boundary condition at the midplane in Eq.(2). Since upper and lower parts of SOL are symmetry about the midplane, both flows along up- and down-stream are expected to pass the midplane with even chance. Consequently, the net flow vanishes there.

$$v_z|_{x=0} = 0 \qquad (8)$$

4. Modeling Region

A computational domain for the edge impurity transport is considered in a lower and outer quadrant of the tokamak SOL with double-null configuration as shown in Fig.1. This lower and outer part of the SOL is chosen as the numerical modeling region in view of its importance in determining radiated power distributions near the divertor plate. It is expected that the severe particle and heat fluxes will be distributed to the outer SOL than to the inner SOL. This region is projected into a one-dimensional configuration for the calculations in this numerical work. A positive x-direction is designated as the direction from the midplane to the divertor plate along the magnetic field line.

Table 1. Basic Specification of KT-2 Tokamak

Major radius	R	1.4 m
Minor radius	a	0.25 m
Aspect ratio	A	5.6
Toroidal field	B_T	3T
Plasma current	I_p	500 kA
Density	n_e	$(0.5\sim1.0)\times10^{20}$ m^{-3}

5. Background Edge Plasma

The background edge plasma fields in the SOL are obtained from a two-dimensional edge plasma transport code, EDGETRAN[2,7,12], in which the design parameters of KT-2 tokamak with a diverted configuration are used for calculations. The basic features of the KT-2 planned in the KAERI (Korea Atomic Energy Research Institute) are given in the Table 1.

For calculations of one-dimensional impurity transport, edge plasma field distributions along magnetic field lines are given by averaging the two-dimensional plasma values over flux function

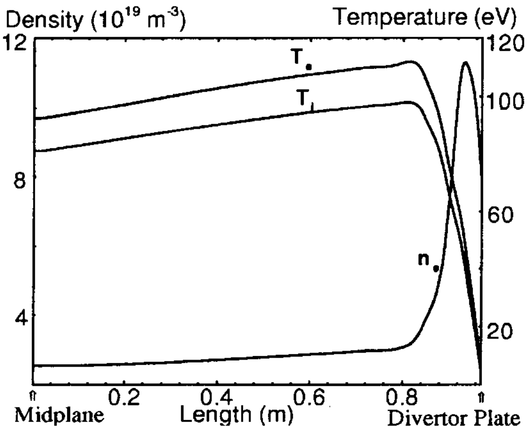

Fig. 2. Distributions of Background Plasma Density and Temperatures Along Magnetic Field Lines in the Tokamak SOL

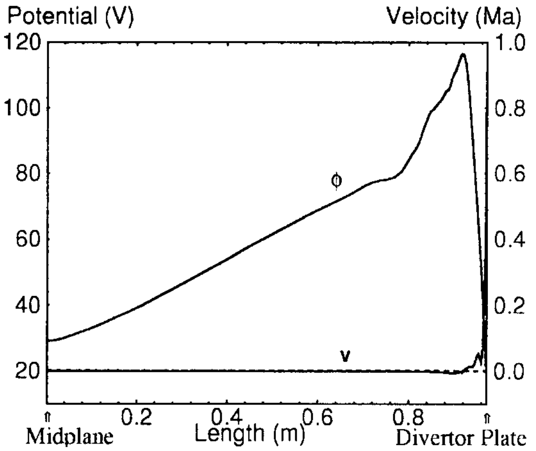

Fig. 3. Profiles of Plasma Velocity and Electrostatic Potential Along Magnetic Field Lines in the Tokamak SOL

in the SOL. In Figs. 2 and 3, the resultant distributions of plasma density, temperature, velocity, and electrostatic potential are plotted along magnetic field lines from the midplane to the divertor plate in the SOL. Fig. 2 shows that the plasma density profile is peaked in front of the divertor plate, which is resulted from the contributions of recycling fuel neutrals (deuterium fuel) to the plasma source in the plate region. Plasma electron and ion temperatures decrease rapidly near the divertor plate due to charge-exchange energy losses to recycling neutrals. Subsequently the temperature gradients of plasma produce the thermal forces directing to the high temperature region. In Fig. 3, plasma ion flow parallel to magnetic field in the SOL is plotted. Plasma flows of about 10^{-3} Ma (mach number) are very inactive in the SOL. However, the ion flows are accelerated by the sheath potential in front of the divertor plate and the ion velocities increase sharply up to an ion sonic speed of about 0.98 Ma. Therefore, the collisional friction forces become significant in front of the divertor plate and cause the acceleration of impurity flows toward the divertor plate. The electric field due to

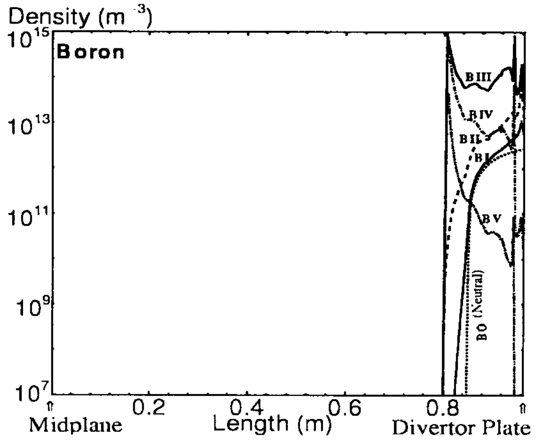

Fig. 4. Boron Ion Density Distributions Along Magnetic Field Lines in the Tokamak SOL with a Boron Neutral Source(BO) in the Divertor Region

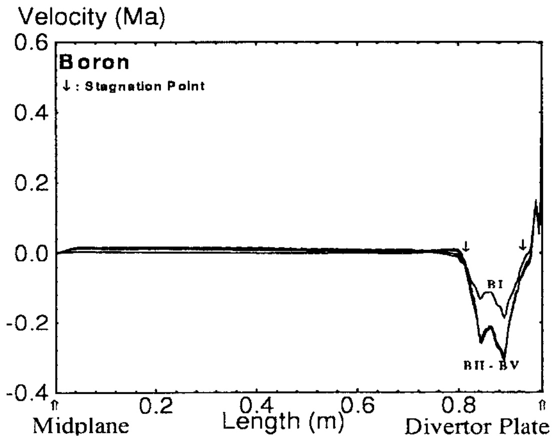

Fig. 5. Boron Ion Velocity Profiles in Mach Values Along Magnetic Field Lines in the Tokamak SOL with a Boron Neutral Source in the Divertor Region

the electron pressure and temperature gradients is characterized by an electrostatic potential profile shown in Fig. 3.

6. Computation Results for Edge Impurities

Calculations for boron and carbon impurity ions are carried out using the one-dimensional impurity transport code developed in the present study. Neutral impurity densities are prescribed by known values in the steady state. Neutrals generated from the first wall and the divertor plate at an initial state develop into multi-charged ions by ionization and some ions are recombined back into neutrals. When the steady state is reached, the neutral density distribution in the SOL can be inferred and used as an input profile to the computation for the numerical analysis.

6.1. Calculations of Boron Impurities

In the first case, boron neutral sources are assumed to be dominantly distributed in the divertor region. Fig. 4 shows that the calculated boron ions are distributed in the vicinity of the neutral source. However, the distributions of boron ions are more broadened than the profile of neutral source, which indicates that the reversal of ion flows is developed in the divertor region. The flow reversal is clearly seen in Fig. 5 for velocity profiles of boron ions along magnetic field lines. Around a narrow region from about 0.8 m to 0.9 m, boron ions move to the negative x-direction toward the midplane.

The second case of boron calculations takes into account an additional boron neutral source near the midplane as given in Fig. 6. In this case, the highly-ionized boron impurities of BIII, BIV, and BV are nearly uniformly distributed in a wide range of positive flow region from the midplane up to 0.8 m. Also the boron impurities are almost fully ionized as BV in this region where the electron temperature (100 ~ 120 eV) is sufficiently high and the ion flows of about 10^{-2} Ma are very slow for the ionization processes to proceed. In both cases, the impurity ions are considerably accumulated at the flow stagnation points, where the flows change their directions near the divertor region as indicated in Figs. 5 and 7. The forces produced by the background plasma determine the

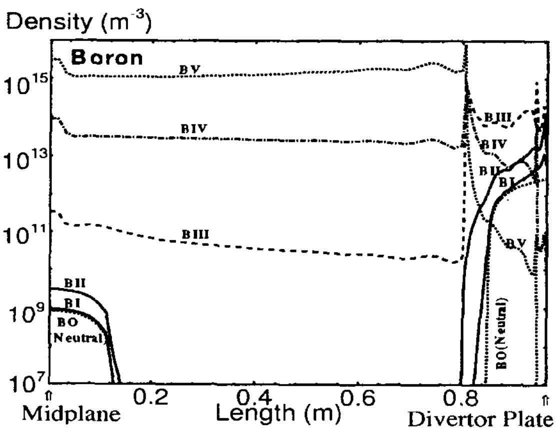

Fig. 6. Boron Ions Density Distributions Along Magnetic Field Lines in the Tokamak SOL with Boron Neutral Sources in the Midplane and Divertor Regions

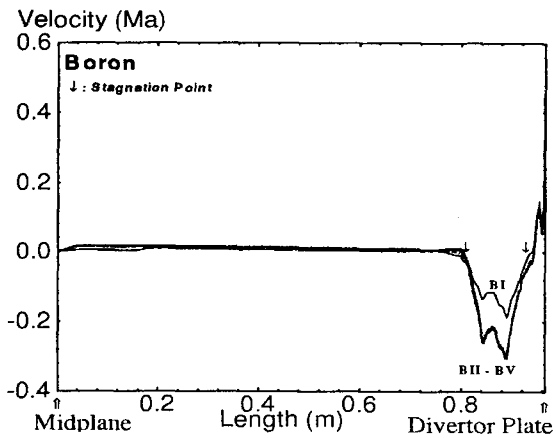

Fig. 7. Boron Ion Velocity Profiles in Mach Values Along Magnetic Field Lines in the Tokamak SOL with Boron Neutral Sources in the Midplane and Divertor Regions

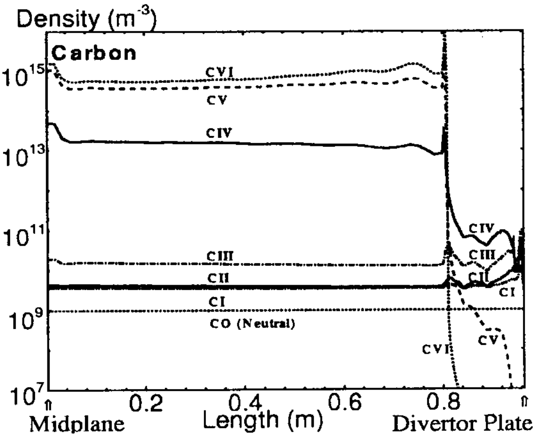

Fig. 8. Carbon Ion Density Distributions Along Magnetic Field Lines in the Tokamak SOL with a Homogeneous Carbon Neutral Source(CO) in the Whole SOL Region

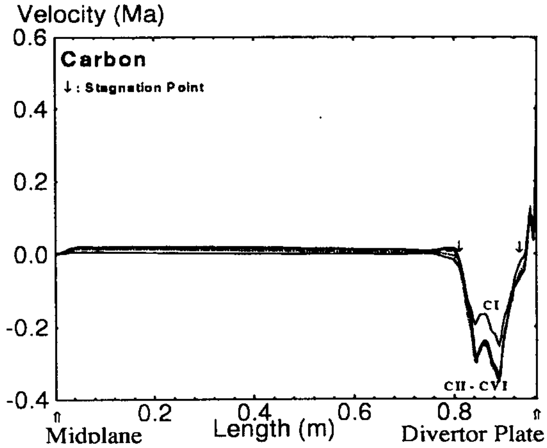

Fig. 9. Carbon Ion Velocity Profiles in Mach Values Along Magnetic Field Lines in the Tokamak SOL with a Homogeneous Carbon Neutral Source in the Whole SOL Region

feature of impurity ion flows. In the vicinity of the divertor plate, both electric and thermal forces directing to the midplane yield the impurity flow reversal, whereas just in front of the divertor plate the plasma velocity increases rapidly so that the collisional friction force drives the impurity flows toward the divertor plate. Therefore, the two opposing forces cause the flow stagnation near the divertor plate and the subsequent impurity accumulation at this point.

6.2. Calculations of Carbon Impurities

Calculated results for carbon ions plotted in Figs. 8～11 show that general trends of density distributions and velocity profiles are similar to those of boron ions. In the first case of carbon calculations, carbon neutrals recycled from the carbonized surfaces of PFC' s are assumed to be homogeneously distributed along the whole SOL. As expected from the boron results mentioned previously, carbon impurities are almost fully ionized and distributed in the positive flow region from the midplane to the first stagnation point as shown in Fig. 8. In this region, the high electron temperatures and the weak ion flows enable the neutrals to be strongly ionized before being reached at the stagnation point. In the divertor plate region including the reverse flows, the recycled neutrals are not strongly ionized since the electron temperature is not sufficiently high and recombinations are comparable with ionizations for high-charged ions of CIV and CV.

In the second case of carbon calculations, strong carbon neutral sources in the divertor region are considered as given in Fig. 10. Strongly ionized carbon impurities are distributed over the upper part of the SOL region. Contrary to the distribution feature in the upper part of the SOL, the accumulations of highly-ionized carbon impurities are considerably reduced in the divertor region. Since the electron temperatures decrease to 2-4 eV in the divertor region, the ionization processes are diminished. Consequently, CII - CIV ions are more dominantly accumulated than CV and CVI in front of the divertor plate as appeared in Fig. 10.

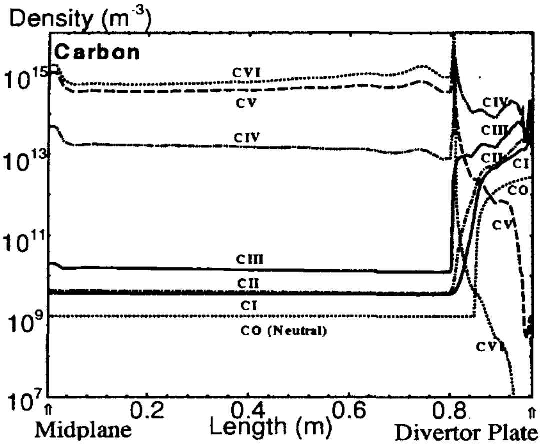

Fig.10. Carbon Ion Density Distributions Along Magnetic Field Lines in the Tokamak SOL with Carbon Neutral Sources in the SOL and Divertor Regions

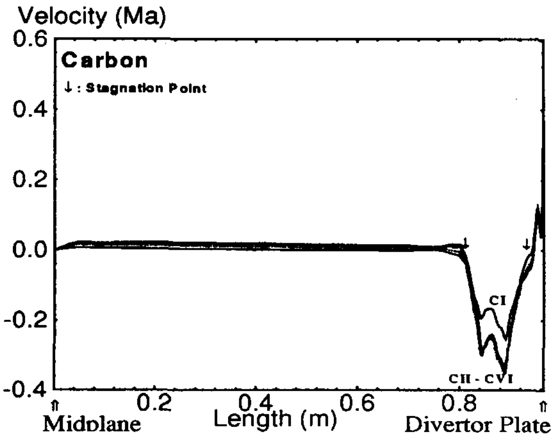

Fig.11. Carbon Ion Velocity Profiles in Mach Values in the Tokamak SOL with Carbon Neutral Sources in the SOL and Divertor Region

7. Comparison of Present Results with Other Work

The calculated results in the present work for KT-2 tokamak are compared with the calculation of one-dimensional impurity transport code developed at Max-Planck-Institut für Plasmaphysik in Germany[3]. Typical background edge plasma values in the ASDEX divertor geometry and the density and flow velocity distributions of oxygen impurity ions along magnetic field lines in the SOL are presented in Figs. 2 and 3 of Ref. [3], respectively. A Gaussian OII source centered at the midplane is assumed in ASDEX calculations, which represents oxygen neutrals released at the wall and immediately ionized. Comparing the ASDEX results for oxygen impurity with the present KT-2 results for boron and carbon impurities in Section 6, there are agreements in general trends of distributions of impurity ions in a qualitative manner. In both cases of ASDEX and KT-2, impurity ions are accumulated at the points where ion flows are retarded and stagnated. Also, it is observed that thermal forces become significant determining the distribution features of impurities in the divertor region where plasma temperature gradients are large.

8. Conclusions

The transport behavior of impurity ions is coupled with the background plasmas in the tokamak scrape-off layer. The plasma temperature gradients build up thermal forces directing to the high temperature side. In the divertor region, thermal forces are dominant over other forces exerting on impurity ions and cause the impurity reversal flow toward the midplane. In front of the divertor plate, a strong collisional friction force is produced due to plasma ions accelerated up to ion sound speed of 0.98 Ma by sheath potentials, and drives the fast impurity ion flows toward the divertor plate. These two opposing forces cause the stagnation points in the impurity ion flows near the divertor. At the stagnation points, the impurity ions are accumulated with the peaked profile. The ionized-state distributions show that strongly ionized impurities such as boron ions of BIV, BV, and carbon ions of CIV, CV, CVI are dominantly distributed in the upper part of the SOL where the electron temperature is high and the ion flows are weak. Near the divertor plate where the electron temperature is relatively low and the flow reversals are produced, the accumulations of strongly ionized impurities are reduced.

In the impurity study, the transport across the magnetic field lines in the tokamak SOL is also important though it is less severer than the transport parallel to magnetic field lines. Since the impurity ions penetrate into the core plasmas by diffusion and drift motions across the magnetic field lines in the SOL, the cross-field transport causes the contamination of core plasmas and the degradation of fusion reactions. Therefore, as the future work, the development of a two-dimensional impurity transport code is required for complete understanding of the transport behavior of impurity ions in the tokamak SOL.

References

1. D. E. Post and R. F. Mattas, Physics of Plasma-Wall Interactions in Controlled Fusion, p.1101, Plenum Press, New York, (1986)
2. Kihak Im, Ph.D. Dissertation, Seoul National University, (1995)
3. J. Neuhauser, W. Schneider, R. Wunderlich, and K. Lackner, Nuclear Fusion, 24, 1 (1984)
4. D. A. Knoll, P. R. McHugh, S. I. Krasheninnikov and D. J. Sigmar, Phys. Plasmas, 3, 1 (1996)
5. K. Borrass and G. Janeschitz, Nuclear Fusion, 34, 9 (1994)
6. S. I. Krasheninnikov and T. K. Soboleva, Phys. Plasmas, 3, 6 (1996)
7. K. Im, D. K. Kim, and S. H. Hong, J. Kor. Phys. Soc. 29, 52 (1996)
8. L. Spitzer, Jr., Physics of Fully Ionized Gases, 2nd ed., Interscience Publishers, New York (1962)
9. P. H. Rutherford, Phys. Fluids, 17, 1782, (1974)
10. S. Chapman, Proc. Phys. Soc. 72, 353, (1958)
11. W. H. Press, S. A. Tuekolsky, W. T. Vetterling and B. P. Flannery, Numerical Recipes in C, p.43, Cambridge University Press, New York, (1992)
12. D. K. Kim, J. M. Ryu, S. H. Hong, and K. Im, J. Kor. Phys. Soc. 31, S223 (1997)