# Simulation Study Using a Virtual Divertor Model on the Supersonic Flow in SOL-Divertor Plasmas Considering the Anisotropic Ion Temperature

非等方イオン温度を考慮したSOL-ダイバータプラズマ中の超音速流に関する 仮想ダイバータモデルを用いたシミュレーション研究

<u>Satoshi Togo</u>, Tomonori Takizuka<sup>a</sup>, Makoto Nakamura<sup>b</sup>, Kazuo Hoshino<sup>b</sup> and Yuichi Ogawa <u>東郷訓</u>, 滝塚知典<sup>a</sup>, 中村誠<sup>b</sup>, 星野一生<sup>b</sup>, 小川雄一

Graduate School of Frontier Sciences, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8568, Japan <sup>a</sup>Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita 565-0871, Japan <sup>b</sup>Japan Atomic Energy Agency, 2-166 Omotedate, Obuchi-aza, O-aza, Rokkasho 039-3212, Japan 東京大学大学院新領域創成科学研究科 〒277-8568 柏市柏の葉5-1-5 <sup>a</sup>大阪大学大学院工学研究科 〒565-0871 吹田市山田丘2-1 <sup>b</sup>日本原子力研究開発機構 〒039-3212 六ヶ所村大字尾駮字表舘2-166

A SOL-divertor plasma simulation code which treats with the Bohm condition self-consistently by introducing the anisotropic ion temperature directly to the plasma fluid model was developed. In order to model the effects of the divertor plate and the accompanying sheath, a virtual divertor (VD) region which has artificial sinks for plasma particle, momentum and energy was introduced and made the periodic boundary condition available. A neutral model which self-consistently matches the VD model has been constructed recently in order to simulate more practical plasmas. The results will be shown in the presentation.

## 1. Introduction

For the commercialization of the fusion reactors, the reduction of the divertor heat load is one of the most important issues [1]. The SOL-divertor plasma transport code packages are expected to be improved to simulate the plasmas more precisely while some results from them show unsatisfactory discrepancies with those from experiments [2].

The momentum transport equation solved in the existing code packages generally includes the second-order derivative parallel ion viscosity term [3]. In solving this equation, the boundary condition (BC) M = 1 at the divertor plate has been used where M is the Mach number while the rigorous Bohm condition only imposes the lower limit as  $M \ge 1$  [4].

The parallel ion viscous flux is the approximated form of the stress tensor  $\pi = 2n(T_{i,l/}-T_{i,\perp})/3$  which was derived under the assumption that  $\pi$  was small enough [4], where plasma density and parallel/ perpendicular ion temperature are denoted by *n* and  $T_{i,l/}/T_{i,\perp}$ , respectively. However, the kinetic simulation showed a remarkable ion temperature anisotropy even for the medium collisionality [5].

We improved our SOL-divertor plasma simulation code [6] by introducing the anisotropic ion temperatures,  $T_{i,//}$  and  $T_{i,\perp}$ , directly to the plasma fluid model. The sum of the effective isotropic ion pressure  $nT_i = n(T_{i,//}+2T_{i,\perp})/3$  and the stress tensor  $\pi$ in the momentum transport equation can be replaced by the parallel component of the ion pressure  $nT_{i,//}$ . Instead of the explicit use of the BC at the divertor plate, we modeled the effects of the divertor plate and the accompanying sheath by using a virtual divertor (VD) model. We set additional mesh points in the artificial region beyond the divertor plates and set artificial sinks for the plasma particle, momentum and energy there. By connecting the calculation domain with the VD region, the periodic BC became available which reduced the numerical difficulty in treating with the nonlinear BCs. We successfully obtained the supersonic plasma flows although neutrals were neglected for simplicity [7].

Recently, we have been constructing a neutral model which self-consistently matches the VD model in order to simulate more practical plasmas. We show here all of the equations describing the whole system although we omit the basic equations and the artificial sinks in the VD region for the plasma which are written in Ref. [7]. The results will be shown in the presentation.

## 2. Neutral Model

Neutrals are divided into two generations; the first-generation (1G) neutrals generated at the divertor plate and transported by the convection at the Franck-Condon (FC) velocity, and the second-generation (2G) neutrals generated in the plasma and transported by the diffusion by charge exchange. The equation for the 1G neutrals is further divided by which divertor plate they are generated at. The equations are as follows;

$$\frac{\partial n_{n,1}^{\text{in}}}{\partial t} - \frac{\partial n_{n,1}^{\text{in}} V_{\text{FC}}}{\partial s} = -\frac{n_{n,1}^{\text{in}}}{\tau_{n,1}} - S_{\text{iz},1}^{\text{in}} - S_{\text{cx},1}^{\text{in}}$$
(1)

$$\frac{\partial n_{n,1}^{\text{out}}}{\partial t} + \frac{\partial n_{n,1}^{\text{out}} V_{\text{FC}}}{\partial s} = -\frac{n_{n,1}^{\text{out}}}{\tau_{n,1}} - S_{\text{iz},1}^{\text{out}} - S_{\text{cx},1}^{\text{out}}$$
(2)

$$\frac{\partial n_{n,2}}{\partial t} + \frac{\partial \Gamma_d}{\partial s} = -\frac{n_{n,2}}{\tau_{n,2}} - S_{iz,2} + S_{rc} + S_{cx,1}$$
(3)

Here, the density of 1G generated at the inner (outer) divertor plate and 2G are denoted by  $n_{n,1}^{in}$  ( $n_{n,1}^{out}$ ) and  $n_{n,2}$ , respectively. The coordinate s is in the poloidal direction defined by  $s = (B_p/B)x$ , where  $B_p$ , B and x are the poloidal component of the magnetic field **B**, the magnitude of **B** and the coordinate parallel to **B**. The pitch of **B**,  $\theta = B_p/B$ , is assumed to be constant for simplicity. The FC velocity is defined by  $V_{\rm FC} = (2\varepsilon_{\rm FC}/m_{\rm i})^{1/2}/2$  with the FC energy  $\varepsilon_{\rm FC} = 3.5$ eV and the mass of ion  $m_i$ . The neutral loss times  $\tau_{n,1}$  for 1G and  $\tau_{n,2}$  for 2G are input parameters. The source terms are defined as  $S^{in(out)}_{iz,1}$  $<\sigma v >_{iz} n^{in(out)}_{n,1} n_e, S^{in(out)}_{cx,1} = <\sigma v >_{cx} n^{in(out)}_{n,1} n_i, S_{iz,2} =$  $\langle \sigma v \rangle_{iz} n_{n,2} n_e$ ,  $S_{rc} = \langle \sigma v \rangle_{rc} n_i n_e$  and  $S_{cx,1} =$  $S^{in}_{cx,1}+S^{out}_{cx,1}$ . The charge neutrality condition is satisfied as  $n_i = n_e = n$ . The rate coefficients for the ionization, the charge exchange and the volume recombination are denoted by  $\langle \sigma v \rangle_{iz}$ ,  $\langle \sigma v \rangle_{cx}$  and  $\langle \sigma v \rangle_{\rm rc}$ , respectively. The diffusion flux  $\Gamma_{\rm d}$  is defined by  $\Gamma_{\rm d} = -D_{\rm n}(\partial n_{\rm n,2}/\partial s)$  whose diffusivity is  $D_{\rm n}$  $= T_{i}/m_{i}(\langle \sigma v \rangle_{cx}n_{i} + \langle \sigma v \rangle_{iz}n_{e} + 1/\tau_{n} 2).$ 

#### 3. Source Terms for the Plasma

The source terms in the plasma basic equations (1)-(5) in Ref. [7] are estimated as follows;

$$S = S^{\text{core}} + m_{i} \left( S_{iz} - S_{rc} \right)$$
(4)

$$M_{\rm m} = m_{\rm i} V_{\rm FC} \sin \theta \left( S_{\rm iz,1}^{\rm out} - S_{\rm iz,1}^{\rm in} + S_{\rm cx,1}^{\rm out} - S_{\rm cx,1}^{\rm in} \right) - m_{\rm i} V \left( S_{\rm cm} + S_{\rm cm} \right)$$
(5)

$$Q_{i,//} = Q_{i,//}^{\text{core}} + (T_i/2)(S_{iz,2} + S_{cx,2})$$

$$+ (m/2)V^2 \sin^2 \theta(S_{iz,2} + S_{iz,2})$$
(6)

$$+ (m_i/2)V_{FC}\sin^2\theta(S_{iz,1} + S_{cx,1})$$

$$- \{(m_i/2)V^2 + T_i/(2)(S_{cx} + S_{rc})\}$$
(6)

$$Q_{i,\perp} = (m_i/2) V_{FC}^2 \cos^2 \theta (S_{iz,1} + S_{cx,1}) + Q_{i,\perp}^{core} + T_i (S_{iz,2} + S_{cx,2}) - T_{i,\perp} (S_{cx} + S_{rc})$$
(7)

$$Q_{\rm e} = Q_{\rm e}^{\rm core} - \varepsilon_{\rm iz} S_{\rm iz} - (3/2) T_{\rm e} S_{\rm rc}$$
(8)

Here, the superscript "core" represents the mass and heat flux from the core plasma. The ionization energy is set as  $\varepsilon_{iz} = 30 \text{ eV}$ . The source terms are defined as  $S_{iz,1} = S^{\text{in}}_{iz,1} + S^{\text{out}}_{iz,1}$ ,  $S_{iz} = S_{iz,1} + S_{iz,2}$ ,  $S_{cx,2} = \langle \sigma v \rangle_{cx} n_{n,2} n_i$  and  $S_{cx} = S_{cx,1} + S_{cx,2}$ .

## 4. Artificial Sources/Sinks for Neutrals



Fig.1. Schematic of the neutral model

The surface recombination of the plasma and the reflection or adsorption of neutrals at the divertor plate can also be expressed by the artificial sources/ sinks so that the periodic BC can also be applied to the neutrals. The equations in the VD region become as follows;

$$\frac{\partial n_{n,1}^{m}}{\partial t} - \frac{\partial n_{n,1}^{m} V_{FC}}{\partial s} = \eta_0 \frac{n}{\tau^{VD}} + \eta_2 \frac{n_{n,2}}{\tau_{n,2}^{VD}}$$
(9)

$$\frac{\partial n_{n,1}^{\text{out}}}{\partial t} + \frac{\partial n_{n,1}^{\text{out}} V_{\text{FC}}}{\partial s} = \eta_0 \frac{n}{\tau^{\text{VD}}} + \eta_2 \frac{n_{n,2}}{\tau_{n,2}^{\text{VD}}}$$
(10)

$$\frac{\partial n_{n,2}}{\partial t} + \frac{\partial \Gamma_{d}}{\partial s} = -\frac{n_{n,2}}{\tau_{n,2}^{\rm VD}}$$
(11)

Here,  $\tau_{n,2}^{VD}$  is the input decay time of the 2G neutrals and adjusted to satisfy the BC that the flux is  $n_{n,2}v_{i,th}$  where  $v_{i,th}$  is the ion thermal velocity defined by  $v_{i,th} = (2T_i/m_i)^{1/2}$ . In VD region,  $D_n$  is given by the interpolation of the values at the plate. The coefficients  $\eta_0$  and  $\eta_2$  are the input emission rates considering the effect of the adsorption. The terms in the RHS of Eq. (9) (Eq. (10)) become zero in the region of V < 0 (V > 0) for the first term and  $\partial n_{n,2}/\partial s > 0$  ( $\partial n_{n,2}/\partial s < 0$ ) for the second term. Figure 1 shows the schematic of this neutral model.

#### Acknowledgments

We are grateful for Dr. K. Shimizu of JAEA, Assoc. Prof. A. Okamoto of Tohoku Univ. and Assoc. Prof. K. Ibano of Osaka Univ. for the fruitful discussions. This work is partly supported by a Grant-in-Aid for Scientific Research from JSPS.

#### References

- [1] ITER Physics Expert Group on Divertor, Nucl. Fusion **39** (1999) 2391.
- [2] A.V. Chankin et al., J. Nucl. Mater. 390-391 (2009) 319.
- [3] S.I. Braginskii, *Reviews of Plasma Physics*, Consultants Bureau (New York, 1965) Vol. 1, p. 205.
- [4] P.C. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*, Institute of Physics Publishing (Bristol and Philadelphia 1999).
- [5] T. Takizuka et al., J. Nucl. Mater. 128-129 (1984) 104.
- [6] M. Nakamura et al., J. Nucl. Mater. 415 (2011) S553.
- [7] S. Togo et al., J. Nucl. Mater. (2014).