

Improvement of One-Dimensional Fluid Modeling of the SOL-Divertor Plasmas and Neutrals Concerning the Anisotropy of Ion Temperature and the Diffusion Coefficient of Neutrals

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1. Introduction

In order to design the divertor of future tokamak fusion reactors, simulation code packages of scrape-off layer (SOL) – divertor plasmas play important roles. For the plasma, a fluid model [1] is often adopted instead of a kinetic model. In the plasma fluid model, a second-order-derivative viscosity term is included in the parallel momentum transport equation which requires the boundary condition for Mach number M at the sheath edge, i.e., $M = 1$ based on the Bohm condition. The viscous flux is an approximated form of stress tensor $\pi = 2n(T_{i,\parallel} - T_{i,\perp})/3$ where n , $T_{i,\parallel}$ and $T_{i,\perp}$ are plasma density, parallel and perpendicular ion temperature, respectively, and was derived on the assumption that the plasma was collisional enough for π to be much smaller than effective isotropic ion pressure $nT_i = n(T_{i,\parallel} + 2T_{i,\perp})/3$ [2]. A kinetic simulation showed, however, that the ion temperature anisotropy of the SOL-divertor plasma was remarkable even in the medium collisional regime [3]. Thus, we developed a one-dimensional (1D) SOL-divertor fluid code which distinguishes between $T_{i,\parallel}$ and $T_{i,\perp}$ [4] by referring to generalized fluid modelling [5]. By introducing anisotropic ion temperatures directly, the parallel momentum transport equation becomes the first-order differential. Consequently, the boundary condition $M = 1$ at the sheath edge becomes unnecessary. Instead of $M = 1$, in order to model the effects of the divertor plate and sheath region, we developed a virtual divertor (VD) model. This model sets artificial sinks for particle, momentum and energy in the artificial region (VD region) between the two divertor plates according to the image of a “waterfall”. It was shown that Bohm condition was automatically satisfied by this VD model [4].

As for the neutral particles, a kinetic Monte-Carlo (MC) model is often used. While kinetic MC model considers every kinetic effect, it has problems of MC noise and long computational time. Fluid model is useful in this point. Thus, we developed a neutral fluid

model which can work with VD model. It was pointed out, however, that the simulation results with a fluid model had a significant difference from those with a kinetic MC model [6]. With the fluid model, spread of the neutral particles in the divertor region seemed to be larger as compared to the kinetic MC model. We suspect that this was caused by the overestimation of the diffusion coefficient without the effect of radial loss of neutral particles.

In this paper, we first explain the numerical models in our code in Sec. 2; plasma fluid model which introduces anisotropic ion temperatures, VD model and neutral fluid model which is self-consistent with the plasma via VD model. In Sec. 3, numerical results are shown. Summary and discussion are described in Sec. 4.

2. Numerical Model

2.1 Plasma fluid model

Basic equations for plasma are given in Ref. [4] in detail and we show here only the equation of parallel momentum transport equation for convenience;

$$\frac{\partial(m_i n V)}{\partial t} + \frac{\partial}{\partial s} (m_i n V^2 + n T_{i,\parallel} + n T_e) = M_m, \quad (1)$$

For the definition of notations, refer to Ref. [4]. In Eq. (1), ion pressure gradient term is described only by its parallel component $n T_{i,\parallel}$ and it does not have the viscosity term. Therefore, the boundary condition at the sheath edge, $M = 1$, is no longer necessary.

2.2 Virtual divertor model

Instead of boundary condition, $M = 1$, we need to reproduce the effects of the divertor plate and sheath. Thus, we developed a virtual divertor (VD) model [4]. It sets an artificial region between the two divertor plates, as shown in Fig. 1, and sets there artificial sinks for particle, momentum and energy according to the image of a “waterfall”. The artificial

particle sink, for example, is given as $S^{VD} = -n/\tau^{VD}$. Here, τ^{VD} is input characteristic time of artificial sinks. For other artificial sinks, refer to Ref. [4]. It was shown that the Bohm condition was automatically satisfied by this VD model [4].

2.3 Neutral model

Neutral particles are divided into two kinds by referring to the FFCD model [7]; recycling

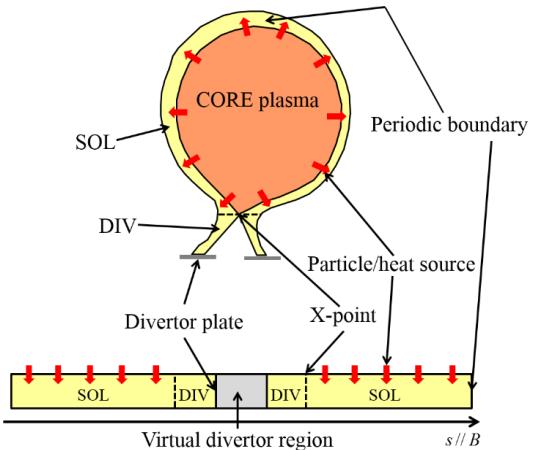


Fig. 1 Schematic picture of virtual divertor model.

neutrals which are generated at the divertor plate by recycling of ions and diffusion neutrals and transported at a constant velocity, and diffusion neutrals which are generated in the plasma by charge exchange of recycling neutrals and volume recombination of plasma and transported by the charge exchange diffusion. Schematic picture of this neutral model in the plasma region is shown in Fig. 2 (a). The equations for recycling and diffusion neutrals density, $n_{n,recy}$ and $n_{n,diff}$, are given as follows, respectively;

$$\frac{\partial n_{n,recy}}{\partial t} + \frac{\partial n_{n,recy} V_{n,recy}}{\partial x} = -n_{n,recy} \nu_{L,recy} - n_{n,recy} \nu_{iz} - n_{n,recy} \nu_{cx} \quad (2)$$

$$\frac{\partial n_{n,diff}}{\partial t} + \frac{\partial}{\partial x} \left(-D_0 \frac{\partial n_{n,diff}}{\partial x} \right) = -n_{n,diff} \nu_{L,diff} - n_{n,diff} \nu_{iz} + n_{n,recy} \nu_{ex} + S_{rc} \quad (3)$$

Here, x is in the poloidal direction. Velocity of recycling neutral is given by $V_{n,recy} = -(2\varepsilon_{FC}/m_i)^{1/2}/2$ with Franck-Condon energy $\varepsilon_{FC} = 3.5$ eV. Radial loss frequencies are defined as $\nu_{L,recy} = 10^{-6}$ s and $\nu_{L,diff} = v_0/d$ where $v_0 = (T_i/m_i)^{1/2}$ is thermal velocity of neutrals and d is the SOL width. The subscripts iz , cx and rc are for ionization, charge exchange and volume recombination, respectively. For the diffusion coefficient, $D_{0,ci} = v_0/(\nu_{cx} + \nu_{iz})$ were used in the preceding studies but, we use $D_{0,ciL} = v_0/(\nu_{cx} + \nu_{iz} + \nu_{L,diff})$, too, which is more strict from the random-walk model point of view. In the VD region, RHSs of Eqs. (2) and (3) are replaced by $S_{n,recy}^{VD} = \eta(n/\tau^{VD}) + \eta_0(n_{n,diff}/\tau_0^{VD})$ and $S_{n,diff}^{VD} = -n_{n,diff}/\tau_0^{VD}$, respectively. By this artificial sink and source, this neutral model becomes self-consistent with the plasma via VD model. Recycling rates η and η_0 are for ions and diffusion neutrals, respectively. Schematic picture of this treatment of neutrals in the VD region is shown in Fig. 2 (b).

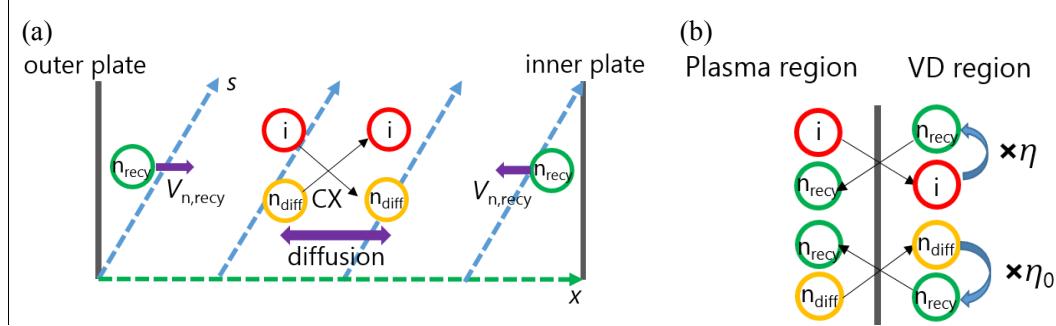


Fig. 2 Schematic picture of the neutral model (a) in plasma region and (b) in VD region.

3. Numerical Results

We investigated the effect of neutrals on the ion temperature anisotropy. By the effects of neutrals, the ion temperature anisotropy is relaxed in both SOL and divertor (DIV) regions as shown in Fig. 3. We also investigated the effect of correction of D_0 with diffusion-only model and recycling/diffusion model by comparing the plasma and neutral density near the divertor

plate between two models for D_0 in the case where $\nu_{cx} \ll \nu_{L,diff}$. With diffusion-only model, in Fig. 4 (a), neutrals spread in wider region in $D_{0,ci}$ case leading to difference in the plasma density profiles. With recycling/diffusion model, in Fig. 4 (b), there was almost no difference. Thus, attention should be paid to the effect of $\nu_{L,diff}$ on D_0 particularly when neutrals are described by the diffusion-only model.

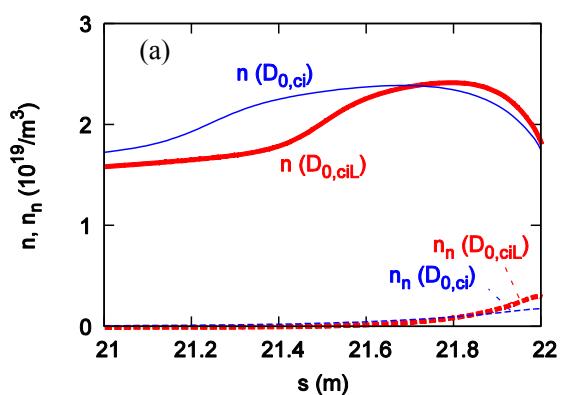


Fig. 4 Plasma and neutral density near the divertor plate at $s = 22$ m (a) by diffusion neutral model and (b) by recycling and diffusion neutral model. $D_{0,ci} = \nu_0 / (\nu_{cx} + \nu_{iz})$ and $D_{0,ciL} = \nu_0 / (\nu_{cx} + \nu_{iz} + \nu_{L,diff})$ are used.

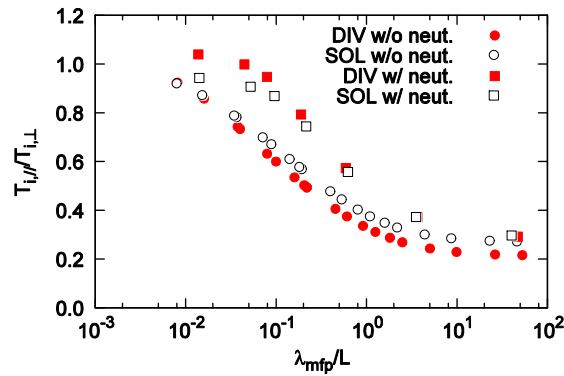
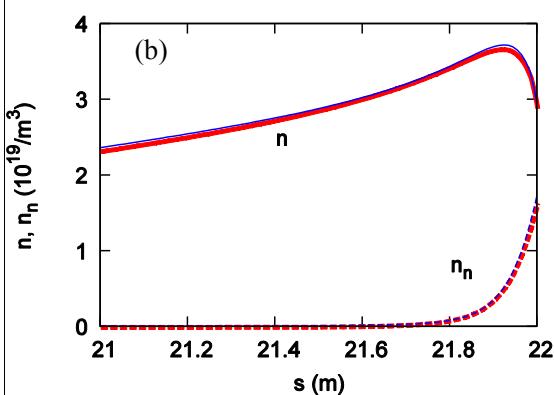


Fig. 3 Anisotropy of ion temperature



4. Summary and Discussion

In order to reproduce the effects of divertor plates and sheath, instead of the boundary condition for Mach number, $M = 1$, we use virtual divertor (VD) model. We developed a neutral model which can work with VD model. The effect of neutrals on the ion temperature anisotropy was investigated. The effect of two models for neutral diffusion coefficient D_0 was also investigated. Difference of profiles became remarkable when neutrals were described by the diffusion-only model.

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