Introduction of kinetic effects to 1-D SOL/divertor plasma fluid simulation by collaborating with a particle model

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1. Introduction

The development of simulation code for the SOL/divertor region is important to control particle and heat in future fusion devices. In this edge plasma modeling, fluid simulations have been mainly used. However, the fluid simulations have not fully reproduced experimental results. [1] One of the causes of this deficiency is the kinetic effects, which cannot be fully considered in the fluid simulation. Therefore, in recent years, development of particle code (PARASOL [2], XGC1 [3], etc.) in edge plasmas has been advanced.

However, particle codes generally have the disadvantage of high computational cost. In order to overcome this disadvantage, we have introduced kinetic effects using particle models in 2-D fluid simulations. [4] In this particle model, plasma parameters antecedently obtained from a fluid simulation [4,5] are translated to electron and ion super particle numbers, their initial velocity distributions, and electric fields. Next, particle trajectories and collisions are calculated in a short time scale. It should be noted that the electric field is not simulated self-consistently. Finally, plasma parameters including kinetic effects, such as heat flux and viscosity, can be obtained correctly and fed back to the fluid simulation.

In this study, we developed 1-D code to establish the basis of this hybrid concept. This model treats a system from the stagnation point to the divertor plate (Fig.1). We describe the fluid and particle models used in the 1-D hybrid model in section2. In section 3, we present the results of simulations comparing between the hybrid model and fluid model for various collisionality. Finally, we describe the summary and discussion.

2. Hybrid model

2.1. Fluid model

1-D fluid equation of SOL/DIV plasma for the direction magnetic field line is given as:

$$\frac{\partial n_i}{\partial \mathrm{t}} + \frac{\partial n_i V}{\partial x} = \mathrm{S} \tag{1}$$

$$\frac{\partial m_i n_i V}{\partial \mathrm{t}} + \frac{\partial}{\partial x}\left[m_i n_i V^2 + (n_i + n_e)T\right] = \mathrm{M} \tag{2}$$

$$\frac{\partial}{\partial \mathrm{t}}\left[\frac{1}{2}m_i n_i V^2 + \frac{3}{2}(n_i + n_e)T\right] + \frac{\partial}{\partial x}\left[\frac{1}{2}m_i n_i V^2 + \frac{5}{2}(n_i + n_e)TV - \kappa_{e,\parallel}\frac{\partial T}{\partial x}\right] = \mathrm{Q} \tag{3}$$

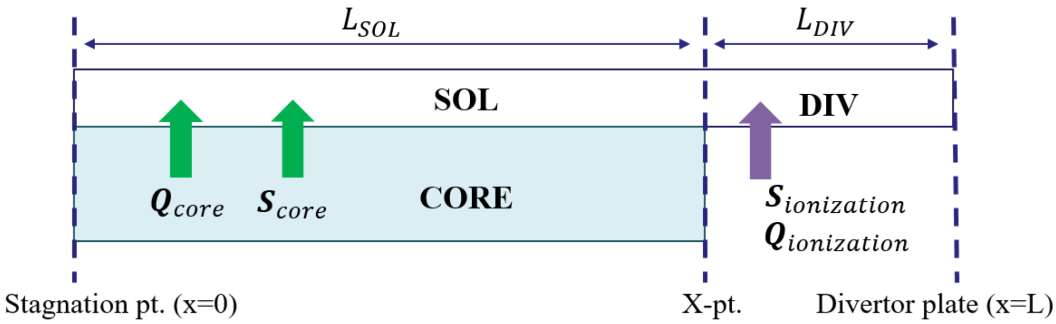

Fig. 1 schematic fluid model

where, $T_i = T_e = T$, $n_i = n_e$, heat conductivity of electrons is $\kappa_{e,\parallel} = 3.16\frac{nT_e\tau_e}{m_e}$. Also, it is assumed that the heat conductivity of ions is sufficiently small. S, M and Q are particles, moments and energy sources, respectively. In this paper, $S = S_{\mathrm{core}} + S_{\mathrm{iz}}$, $M = 0$, $Q = Q_{\mathrm{core}} + Q_{\mathrm{iz}}$. Since S_{core} and Q_{core} are source from CORE, they apply only to the SOL area and give as parameters. On the other hand, $S_{\mathrm{iz}} = R_{\mathrm{recy}} \times S_{\mathrm{core}} \cdot L_{\mathrm{SOL}}/\{(1 - R_{\mathrm{recy}}) \cdot L_{\mathrm{DIV}}\}$, $Q_{\mathrm{iz}} = 2\varepsilon_{\mathrm{FC}} \times S_{\mathrm{iz}}$ are given only to the divertor region, considering only the effect of ionization alone at this time as recycling. The boundary condition in the fluid model are $\frac{\partial \mathrm{T}}{\partial \mathrm{x}} = 0, V = 0$ at the stagnation point, and the divertor plate uses Bohm condition at the divertor plate (sheath entrance) in which the plasma flow velocity becomes the ion sound speed.

2.2. Particle model

In order to confirm the consistency of each model, particle model is calculated under the same conditions as fluid model.

First, number of super-particles and their initial shifted Maxwellian velocities at each cell are determined using n, T and V calculated antecedently by the fluid model. In order to reduce the calculation cost, the self-consistent simulation of the electric field is not taken, but a fixed electric field based on the fluid model is used. The electric field parallel to the magnetic field is calculated by the following equation of the electron momentum balance. Here, no electric current is assumed.

$$E_{\parallel} = -\frac{0.71}{e}\frac{\partial(eT_e)}{\partial x_{\parallel}} - \frac{1}{en}\frac{\partial p_e}{\partial x_{\parallel}} \quad (4)$$

Second, particle trajectories are calculated with the similar method in PARASOL [2]. The guiding center model for electrons, which follows the motion of gyro center, is used. While, for ions, the gyro motion model, which follows the entire movement including the gyration motion is employed. Third, the collision calculation is treated by the Symmetric model [6], which can treat two body collisions between different weight particles. For simplicity, all particles have the same weight w in this study. Representing the particle and the energy sources from the core plasma, super-particles are introduced to random positions of the SOL region. The number of the super-particles are $N_{\rm core} = \frac{S_{\rm core}}{w}\Delta t$ for each time step. The velocity distribution of the super-particles is given from the Maxwellian distribution of the temperature calculated at the fluid model.

Furthermore, at the present time, only the effect of ionization is dealt with in the same way as fluid calculation for recycling. At each step, the number of particles incident N on the divertor plate is used to determine the number of recycled particles $N_{\rm iz} = R_{\rm recy} \times N (0 < R_{\rm recy} < 1$ is a recycling rate). Each recycling particle is returned to the divertor region, an initial velocity of $V_{\rm iz} = -(2\varepsilon_{\rm FC}/m_i)^{1/2}/2$ is given according to the Maxwell distribution with Franck-Condon energy $\varepsilon_{\rm FC} = 3.5\text{eV}$.

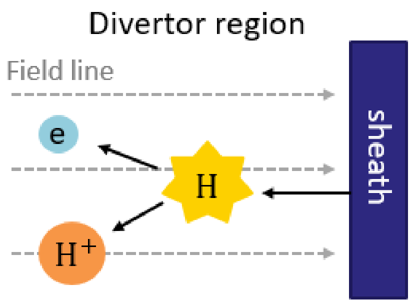

Fig. 2 Particle recycling model

As a boundary condition, all particles are reflected at the stagnation point. At the divertor plate (sheath entrance), particles are eliminated or reflected according to the boundary conditions. When ions reach the boundary mesh, all ions enter the wall and are evacuated. On the other hand, when electrons reach the boundary mesh, the incident energy of an electron determines the incidence or reflection as follows.

$$\text{Incident high energy particle: } m_e v_{e,\parallel}^2/2 \geq e\phi_s(t) \qquad (5a)$$

$$\text{Reflective low energy particle: } m_e v_{e,\parallel}^2/2 \leq e\phi_s(t) \qquad (5b)$$

The sheath potential $\phi_s(t)$ is updated as follows according to the number of electron and ion particles incident in the wall. Also, the initial value is $\phi_s(t) = 0$.

$$\phi_s(t + \Delta t) = \phi_s(t) - \alpha T_e/e \qquad (6)$$

Here, number of incident electron particles ($\mathrm{d}N_e$) and ion particles ($\mathrm{d}N_i$) should become equal, $\mathrm{d}N_i = \mathrm{d}N_i$. For this sake, the potential control parameter α is chosen as the following equation.

$$\alpha = (\mathrm{d}N_i - \mathrm{d}N_e)/(\mathrm{d}N_i + \mathrm{d}N_e) \qquad (7)$$

3. Numerical results

In this section, results of the fluid model and the fluid/particle hybrid model are compared. To investigate the dependence of the collisionality, we increase the variance value in the binary collision calculation, Eq. (11) in Ref. [2], by 1 time, 10 times, and 100times.

Fig. 4 shows calculated profiles of density and temperature for a medium recycling divertor $R_{\rm recy}$ = 0.8. Particle model with higher artificial collisionality (vari$\times 10$ and $\times 100$) shows similar profiles to the fluid model expect in the divertor region. The difference in the divertor region can be caused by the simplified sheath model and/or the recycling model. In case of the lowest collisionality (vari ×1), both density and temperature gradient become smaller. Therefore, it can be seen that the collisionality and heat conductivity of electrons are in inverse proportion.

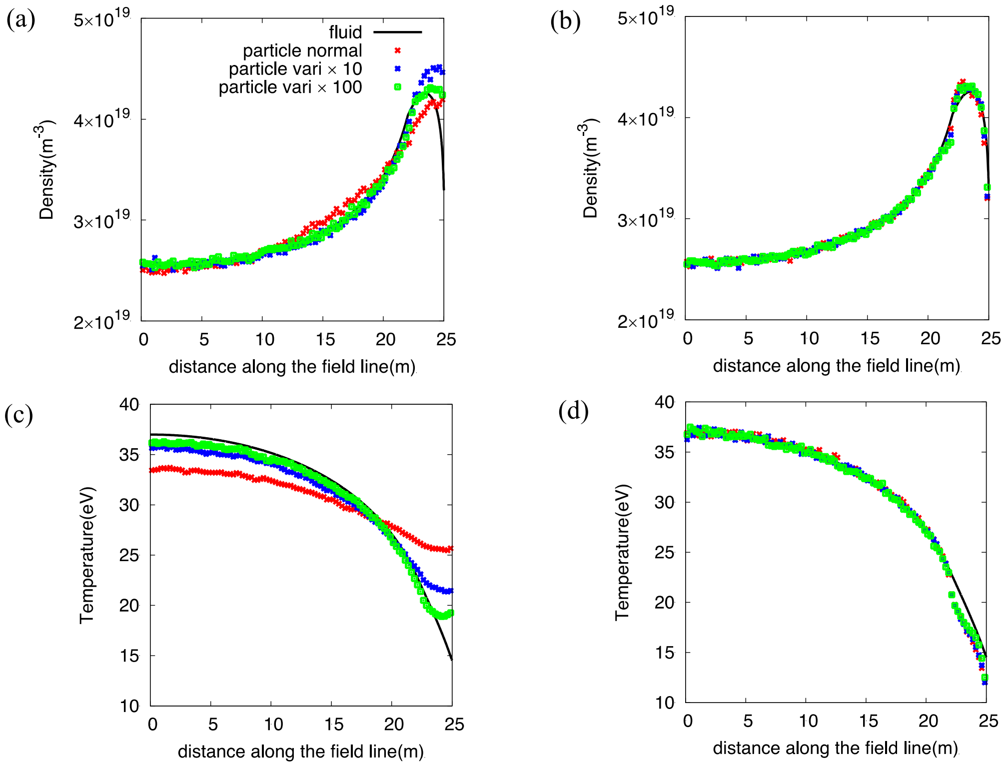

Fig. 3 Collisionality dependence of (a)electron density, (b)ion density, (c)electron temperature and (d)ion temperature

4. Summary and Conclusion

We developed a 1-D fluid/particle hybrid code. In this paper, in order to confirm the validity of the code, conditions (such as each source inflow range and recycling) within fluid/particle calculation were unified. In addition, the variance in the collision calculation was multiplied by a constant, and particle calculation was performed with the degree of collision changed intentionally. We evaluated the collision rate dependence of the temperature and density of electrons and ions (H^+) by comparing the results of different collisionality. As the collisionality decreases, the gradients of the electron density and temperature decrease and tend to deviate from the results of fluid model. From this result, it is implied that electron heat conductivity is increased by the decrease of collisionality.

References

[1] A.V. Chankin et al., J. Nucl. Mater. 390-391 (2009) 319

[2] T. Takizuka, Plasma Phys. Control. Fusion 59 (2017) 034008

[3] C.S. Chang et al., Phys. Plasmas 15 (2008) 062510

[4] A. Tanaka, K. Ibano, M. Obiki, et al., Introduction of kinetic effects to fluid simulation by a particle model, 60th APS DPP (Portland, US, 2018)

[5] H. Kawashima et al., Plasma Phys. Control. Fusion 49 (2007) 77

[6]. A. Tanaka et al., Contrib. Plasma Phys. 58(2018) 451