§3. Research on Advanced Operation and Control for Fusion Core Plasmas — SOL-divertor Simulation —

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We developed a one-dimensional plasma fluid code for scrape-off layer (SOL) and divertor region in order to contribute to improvement of the fluid modeling of SOL-divertor plasma by focusing on self-consistent treatment of the boundary condition at the sheath region in front of the divertor plate. In conventional fluid codes, by assuming that the ion temperature anisotropy is small, Braginskii's equations are introduced where the parallel ion viscosity term given by a second-order derivative in space is employed in the parallel momentum transport equation. In order to solve this equation, the Mach number at the divertor plate M must be given as the boundary condition like $M = 1$ based on the Bohm condition. But, rigorously speaking, this boundary condition is inadequate, since the Bohm condition is given by the inequality $M \geq 1$. In addition, supersonic plasma flows at the divertor plate were observed by kinetic simulations. To solve the Bohm condition self-consistently, we have introduced a rigorous formula for parallel momentum transport equation only with a first-order derivative in space, and parallel and perpendicular ion temperatures have been independently solved.

$$\frac{\partial m_{\mathrm{i}} n V}{\partial t} + \frac{\partial}{\partial s}\left(m_{\mathrm{i}} n V^{2} + n T_{\mathrm{i},//} + n T_{\mathrm{e}}\right) = M_{\mathrm{m}},$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2} m_{\mathrm{i}} n V^{2} + \frac{1}{2} n T_{\mathrm{i},//}\right) + \frac{\partial}{\partial s}\left(\frac{1}{2} m_{\mathrm{i}} n V^{3} + \frac{3}{2} n T_{\mathrm{i},//} V + c q_{\mathrm{i},//}^{\mathrm{eff}}\right)$$
$$= Q_{\mathrm{i},//} + \frac{n\left(T_{\mathrm{i},\perp} - T_{\mathrm{i},//}\right)}{\tau_{\mathrm{rlx}}} + \frac{m_{\mathrm{e}}}{m_{\mathrm{i}}} \frac{n\left(T_{\mathrm{e}} - T_{\mathrm{i},//}\right)}{\tau_{\mathrm{e}}} - V \frac{\partial n T_{\mathrm{e}}}{\partial s},$$

$$\frac{\partial n T_{\mathrm{i},\perp}}{\partial t} + \frac{\partial}{\partial s}\left(n T_{\mathrm{i},\perp} V + (1 - c) q_{\mathrm{i},\perp}^{\mathrm{eff}}\right)$$
$$= Q_{\mathrm{i},\perp} - \frac{n\left(T_{\mathrm{i},\perp} - T_{\mathrm{i},//}\right)}{\tau_{\mathrm{rlx}}} + \frac{2 m_{\mathrm{e}}}{m_{\mathrm{i}}} \frac{n\left(T_{\mathrm{e}} - T_{\mathrm{i},\perp}\right)}{\tau_{\mathrm{e}}},$$

Here, t represents the time and s is the coordinate in the parallel direction to the magnetic field. The effective isotropic ion temperature is defined by $T_{\mathrm{i}} = (T_{\mathrm{i},//} + 2T_{\mathrm{i},\perp})/3$. Since the Mach number at the divertor plate is determined self-consistently by the upstream condition, it is no longer necessary to be given as the boundary condition.

In addition, in order to model the effects of the sheath region in front of the divertor plate, we developed and introduced a "virtual divertor (VD) model". In this model, we set an artificial region (VD region) beyond the divertor plates and set artificial sinks for particle, momentum and energy there according to the image of the "waterfall", as shown in Fig. 1.

We confirmed that the Bohm condition was automatically satisfied by this VD model. Supersonic flows demonstrated in the kinetic simulations were also observed with our fluid code, as shown in Fig. 2. It was shown that the profiles in the plasma region were not affected by the strength of the artificial sinks in the VD region and that the sheath heat transmission factors can be adjusted to the values from sheath theory with VD model. Meanwhile, in the SOL-divertor system, it was shown by kinetic simulations that the ion temperature anisotropy became remarkable in the low collisional regime. The same tendency was obtained with our fluid code. The validity of the model for parallel ion viscosity term was also checked, leading to the conclusion that introduction of the anisotropic ion temperature was significant for SOL-divertor fluid modeling. This VD model accompanied by anisotropic ion temperatures might be worthwhile to deal with the sheath region in front of the divertor plate, because the Bohm condition and sheath heat transmission factors can be self-consistently determined.

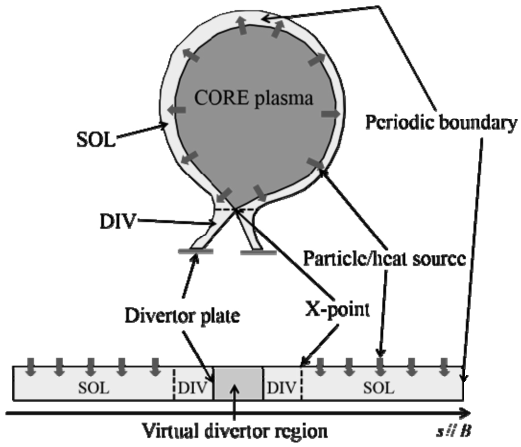

Fig. 1 Schematic drawing of the connected VD region. By connecting the VD region and using periodic boundary condition, a problem of boundary conditions at the edge of the system is automatically avoided.

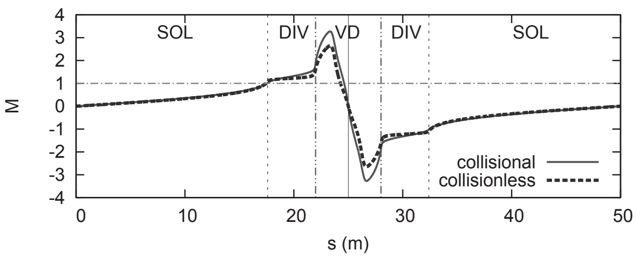

Fig. 2 Profiles of Mach number M for collisional (solid lines) and collisionless (broken lines). Vertical broken lines represent the divertor plates at s = 22 m and 28 m and the region between them is the VD region. X-points are at s = 17.6 m and 32.4 m. Since we employ the same conditions for inner and outer SOL-divertor plasmas, the simulation results are symmetric at s = 25 m.