§15. 1D Modeling of LHD Divertor Plasma and Hydrogen Recycling

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Characteristics of a divertor plasma controls the impurity transport, which causes undesirable radiation cooling in the core plasma. Therefore, the physical understanding of the divertor plasma and its modeling for simulation studies on LHD boundary plasmas is important issue. We present a 1D model of the divertor plasma and neutrals. This model is intended to be employed in our future simulation studies as a model of divertor legs to connect the following two simulation codes; EMC3 code[1] for the ergodic layer and ERO code[2] for the plasma-surface interactions at the divertor. We use the same Braginskii-type two fluid equations as in the previous work, "1D fluid model of plasma profiles in the LHD divertor leg," to describe the divertor plasma. The same notations are used here.

In order to include interactions of plasma, hydrogen molecules and atoms, we choose five dominant reactions in the divertor plasma. (d1) $H_2 + e^- \rightarrow 2H + e^-$, (d2) $H_2 + e^- \rightarrow H^+ + H + 2e^-$, (cx) $H + H^+ \rightarrow H^+ + H$, (iz) $H + e^- \rightarrow H^+ + 2e^-$, (rc)$H^+ + 2e^- \rightarrow H + e^-$. The fist and second reactions, (d1) and (d2), represent the dissociation of hydrogen molecules to atoms. The last three reactions, (cx), (iz) and (rc), represent charge exchange, ionization and recombination, respectively. The rate coefficient of these reactions[3,4] are denoted by $\langle\sigma_{d1}v\rangle$, $\langle\sigma_{d2}v\rangle$, $\langle\sigma_{cx}v\rangle$, $\langle\sigma_{iz}v\rangle$ and $\langle\sigma_{rc}v\rangle$, respectively.

We classify the neutrals into four components; molecules released from the divertor plate, dissociated atoms from the molecules, charge exchange atoms and recombination atoms. The particle speed of each component is treated as a constant; v_m, v_d, v_{cx} and v_{rc}, respectively. The density of each component is denoted by n_m, $n_d^\pm$, $n_{cx}^\pm$ and $n_{rc}^\pm$, respectively. The superscript '±' corresponds to two components with opposite direction, i.e. positive and negative velocity on s-coordinate. They have each characteristic temperature, or energy, determined from their sources. The molecule temperature T_m is the same as that of the divertor plate. The temperature of dissociation atoms is determined from the Frank-Condon dissociation energy. The temperatures of charge exchange and recombination atoms, T_{cx} and T_{rc}, are determined from the averaged energy of the generated atoms by each processes over $s = 0$ to $l_\P$. The velocity of each component is calculated from the corresponding temperature. The angle of the magnetic field measured from the surface normal on the divertor plate was denoted by φ and used to obtain the equivalent velocity of molecules.

The particle balance equations of neutrals are given by

$$-v_m \frac{dn_m}{ds} = (\langle\sigma_{d1}v\rangle + \langle\sigma_{d2}v\rangle)\, n_m n_e, \quad (1)$$

$$\pm v_d \frac{dn_d^\pm}{ds} = (2\langle\sigma_{d1}v\rangle + \langle\sigma_{d2}v\rangle)\, n_m n_e - (\langle\sigma_{iz}v\rangle n_e + \langle\sigma_{cx}v\rangle n_i)\, n_d^\pm, \quad (2)$$

$$\pm v_{cx} \frac{dn_{cx}^\pm}{ds} = (1 - r_{pl})\frac{v_{cx} \pm v}{2v_{cx}}\langle\sigma_{cx}v\rangle n_a n_i - (\langle\sigma_{iz}v\rangle n_e + \langle\sigma_{cx}v\rangle n_i)\, n_{cx}^\pm, \quad (3)$$

$$\pm v_{rc} \frac{dn_{rc}^\pm}{ds} = (1 - r_{pl})\frac{v_{rc} \pm v}{2v_{rc}}\langle\sigma_{rc}v\rangle n_e n_i - (\langle\sigma_{iz}v\rangle n_e + \langle\sigma_{cx}v\rangle n_i)\, n_{rc}^\pm, \quad (4)$$

where the total density of hydrogen atoms were denoted by $n_a \equiv n_d^+ + n_d^- + n_{cx}^+ + n_{cx}^- + n_{rc}^+ + n_{rc}^-$ in Eq. (3). Therefore the boundary conditions of neutrals are given by $n_{m1}v_m = n_1 v_1/2$, $n_{d1}^+ = n_{d1}^-$, $n_{cx1}^+ = n_{cx1}^-$, and $n_{rc1}^+ = n_{rc1}^-$ at $s = l_\P$. The particle loss of hydrogen atoms was introduced as a constant ratio r_{pl} in Eqs. (3) and (4).

We developed a numerical code to solve the plasma equations and the neutral equations, (1) – (4), self-consistently. The density profiles of neutrals near the divertor plate, $s = 2.5$ to 3, are shown in Fig. 1, where the three curves correspond to their sources; hydrogen molecules released from the wall surface, atoms dissociated from molecules and generated through charge exchange processes. The recombination processes are negligible in this case because the plasma temperature is relatively high. The amount of neutrals corresponding to each source is obtained easily and it is one of advantages of our model. Since the molecules and dissociation atoms are relatively slow, their decay length is short, ~ 0.1 [m] along the magnetic fields, while the charge exchange atoms have longer decay length, ~ 0.3 [m].

The dependence of the heat flux on the plasma density was also studied. In the low density case, the plasma loses its energy by ionization and charge exchange, but effect of the loss on the heat flux is small. For the high density case the ionization loss and impurity cooling becomes large and the heat flux decreases by 40% when the plasma density at the upstream boundary is high. We confirmed that the ion energy is transfered to electron and it is lost by ionization and impurity radiation.

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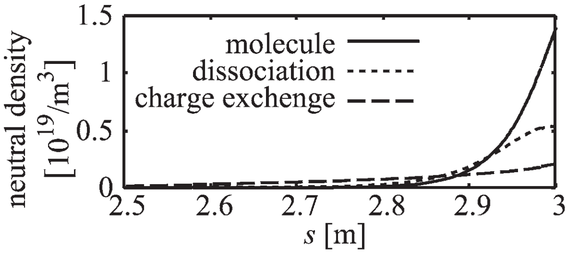

Fig. 1: Density profiles of neutrals; hydrogen molecules, atoms generated by dissociation and charge exchange.