Effects of Neutral Particles on the Stability of the Detachment Fronts in Divertor Plasmas*)

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Operation with detached divertor plasmas is considered to be a hopeful way in order to reduce the divertor heat load in the next generation tokamaks. The physical mechanism of detached divertor plasmas, however, has not fully been understood yet. We have studied them with a one-dimensional divertor model. Detached divertor plasmas have been successfully reproduced by introducing a self-consistent neutral model. The flows of particles and heat from the core plasma were investigated in the detached regime. Also investigated were the conditions of the recycling rate and neutral loss time constant where the detached regime occurred.

Keywords: divertor heat load, detached divertor plasma, detachment front, plasma fluid model, self-consistent neutral model, recycling rate, neutral loss

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1. Introduction

Reduction of the divertor heat load is one of the crucial issues in designing the next generation tokamaks such as ITER and DEMO. In order to resolve this issue, detached divertor plasmas are considered to be a promising way [1]. The physical mechanism of them, however, has not fully been understood yet.

In modeling SOL-divertor plasmas, two-dimensional (2D) codes, such as SONIC [2] and SOLPS [3], and point models have been used. It is considered, however, that 2D codes are computationally massive to focus on studying each physical phenomenon in plasmas. On the other hand, the latter models are very easy, but have not reproduced detached divertor plasmas so far. Thus we have been using the one-dimensional (1D) codes [4, 5], which are computationally lighter than 2D ones, in order to gain physical insights of detached divertor plasmas.

In our previous works [6–8], we reproduced partially detached divertor (PDD) plasmas, which will be adopted for ITER operation scenarios [9], with a 'multi-layer (ML)' 1D model. It was shown that the cross-field heat transport, which have been proven to significantly affect behaviors of the PDD plasmas [10, 11], prevented the detachment front in the inner flux tube from moving upstream and resulting in X-point MARFE. In order to focus on the effects of the cross-field heat transport, we had introduced a simple neutral model where the neutral flux, given by the recycling of the ion flux plus auxiliary gas puffing, decayed exponentially with the local mean free path of the ionization reaction or the geometric mean of mean free paths of the ionization and charge exchange reactions. In this paper, in order to focus on the effects of neutrals on detachment fronts, we adopted a time dependent self-consistent neutral model. The neutral flux is assumed to be composed of convection with a constant flow velocity and diffusion involving the charge exchange reaction [3]. Source term due to volume recombination reaction and loss/source term due to the cross-field neutral transport are involved in it. The total number of ion and neutral particles becomes conserved.

The geometry of the 1D divertor model and the plasma fluid equations are shown in Sec. 2.1. Comparison between old neutral model and new one is shown in Sec. 2.2. As simulation results, we first show the difference in the neutral density profiles resulted from each transport mechanism introduced in the neutral model in Sec. 3.1. In Sec. 3.2, we show a simulation result of the detached regime and the flows of particles and heat from the core plasma. Also is shown there the conditions of the recycling rate and neutral loss time constant where the detached regime occurs. Finally, in Sec. 4, we present a conclusion.

2. Model

2.1 Geometry and plasma fluid equations

The 1D divertor model is used to analyze a SOL-divertor plasma along the magnetic field shown in Fig. 1. We introduce x-axis along the magnetic field and set the

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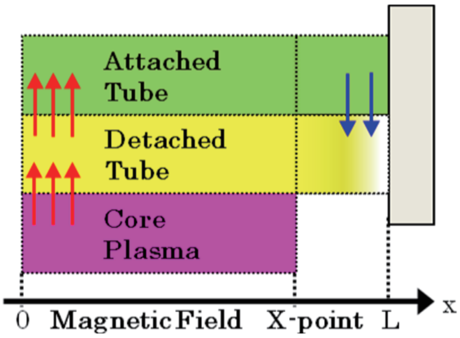

Fig. 1 Schematic picture of (multi-layer) 1D divertor model.

stagnation point and the divertor plate to be $x = 0$ and $x = L$, respectively. The particle and heat flux from the core plasma are considered in the SOL region. We intend to simulate PDD plasmas with ML 1D model, however, we did only single tube analyses in this paper.

The 1D transport equations are given as follows [12];

$$\frac{\partial(mn)}{\partial t} + \frac{\partial(mnV)}{\partial x} = mS, \tag{1}$$

$$\frac{\partial(mnV)}{\partial t} + \frac{\partial(mnV^2 + P)}{\partial x} = M, \tag{2}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}mnV^2 + 3nT\right) + \frac{\partial}{\partial x}\left\{\left(\frac{1}{2}mnV^2 + 5nT\right)V - \kappa_e \frac{\partial T}{\partial x}\right\} = Q. \tag{3}$$

Here, the density n, the flow velocity V, the temperature T of ions and electrons are assumed to be equal, respectively. $P(= 2nT)$ is the plasma pressure and κ_e is the parallel electron heat conductivity. The source terms are given as follows;

$$S = S_{\rm core} + \langle\sigma_{\rm iz}v\rangle\, n_n n_e - \langle\sigma_{\rm rc}v\rangle\, n_i n_e, \tag{4}$$

$$M = -mV\,\langle\sigma_{\rm cx}v\rangle\, n_i n_n - mV\,\langle\sigma_{\rm rc}v\rangle\, n_i n_e, \tag{5}$$

$$Q = Q_{\rm core} - E_{\rm iz}\,\langle\sigma_{\rm iz}v\rangle\, n_n n_e - L_z n_{\rm imp} n_e - \left(\frac{mV^2}{2} + \frac{3}{2}T\right)\langle\sigma_{\rm cx}v\rangle\, n_i n_n - (E_{\rm rc} - 13.6_{\rm [eV]})\,\langle\sigma_{\rm rc}v\rangle\, n_i n_e. \tag{6}$$

Here, $S_{\rm core}$ and $Q_{\rm core}$ are the input particle and heat flux from the core plasma, respectively. $E_{\rm iz}$ represents the ionization energy (13.6 eV) plus the radiation loss from excited atom so that it is set to be 30 eV. The impurity is assumed to be carbon and its cooling rate L_z is treated in non-coronal equilibrium [13] and the impurity density profile is given by $n_{\rm imp} = r_{\rm imp} n_i$ with $r_{\rm imp}$ set to be 3%. $E_{\rm rc}$ represents the energy loss by the volume recombination involving radiative recombination and three-body recombination. For the electron temperature lower than 5.25 eV, the three-body recombination dominates so that the volume recombination reaction acts as net heat source.

We omit the explanation of the boundary conditions here since they are the same as our previous works [6–8].

2.2 The neutral model

In our previous works [6–8], in order to focus only on the effects of cross-field transport, we had introduced a simple neutral model as follows;

$$n_{n,j} = n_{n,j+1}\exp(-\Delta s/\lambda), \tag{7}$$

$$\lambda = \lambda_{\rm iz} \quad \text{or} \quad \sqrt{\lambda_{\rm iz}\lambda_{\rm cx}}. \tag{8}$$

The subscript j represents the mesh number and Δs is the mesh width in the poloidal direction. The ionization and charge exchange mean free paths are denoted by $\lambda_{\rm iz}$ and $\lambda_{\rm cx}$, respectively. Equation (7) is based on the steady state continuity equation without volume recombination source. The neutral decay length can be chosen from $\lambda_{\rm iz}$ and $\sqrt{\lambda_{\rm iz}\lambda_{\rm cx}}$ as Eq. (8).

In order to focus on the effects of neutrals in turn, we have introduced a time dependent self-consistent neutral model instead of our previous simple neutral model as follows;

$$\frac{\partial n_n}{\partial t} + \frac{\partial \Gamma_n}{\partial s} = -\langle\sigma_{\rm iz}v\rangle\, n_n n_e + \langle\sigma_{\rm rc}v\rangle\, n_i n_e - \frac{n_n}{\tau_n}, \tag{9}$$

$$\Gamma_n = \alpha(n_n v_{\rm FC}) + \beta\left(-\lambda_{\rm cx} v_{\rm th}\frac{\partial n_n}{\partial s}\right). \tag{10}$$

Here, Γ_n is the flux of neutral particle, $v_{\rm FC}$ is the velocity of neutral particles which have Franck-Condon energy (3.2 eV) which has negative value and $v_{\rm th}$ is the local thermal velocity of the plasma. The neutral flux is assumed to be composed of convection with a constant flow velocity $v_{\rm FC}$ and diffusion involving the charge exchange reaction [3] and each effect is controlled by changing the values of input parameters α and β. The third term in the right hand side of Eq. (9) represents cross-field neutral particle loss term whose time constant τ_n is an input parameter. By adding the volume recombination source term newly, the number of ions and neutrals become self-consistently balanced.

At the stagnation point and the divertor plate we use the following boundary conditions, respectively;

$$\Gamma_{n,\rm stag} = 0, \tag{11}$$

$$\Gamma_{n,\rm div} = -\eta_{\rm trap}(nV)_{\rm div}. \tag{12}$$

Here, $\eta_{\rm trap}$ is the recycling rate which is also an input parameter.

3. Results

In the following simulation results, the parameters are chosen to be ASDEX Upgrade like [14]. The connection length L is 22 m and the position of X-point is 17.6 m. The particle and heat flux from the core plasma are $6.0\times10^{21}\ {\rm s}^{-1}$ and 4 MW, respectively. The area of the separatrix magnetic surface is $40\ {\rm m}^2$ and the thickness of the SOL is uniformly 2 cm.

3.1 Effects in the neutral model

In order to investigate how the neutral profile is affected by the effects introduced newly. First, we investi-

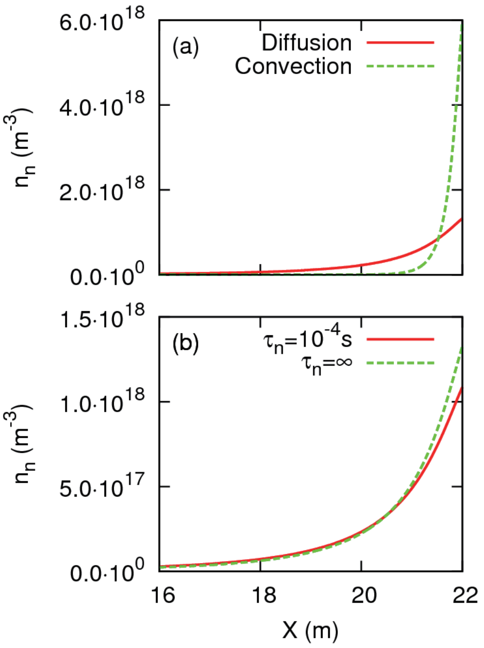

Fig. 2 Neutral profiles for different cases; (a) diffusion-dominant case, $(\alpha,\beta) = (0, 1)$ (red), and convection-dominant case, $(\alpha,\beta) = (1, 0)$ (green), (b) with cross-field neutral loss term (red) and without it (green).

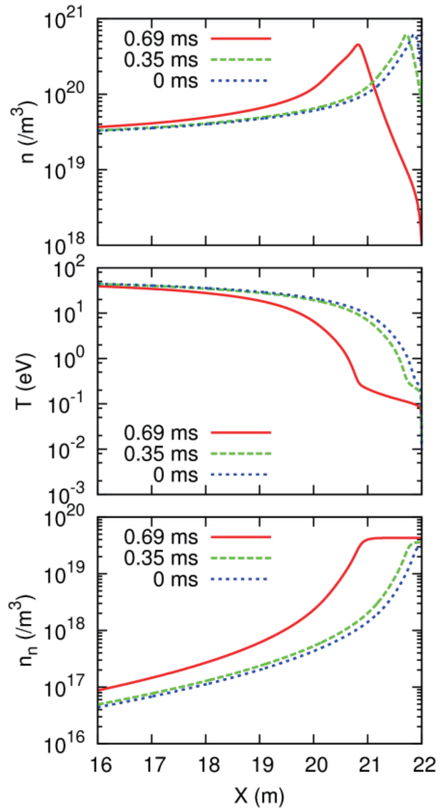

Fig. 3 Time variation of the spatial profiles of plasma parameters in the detached regime.

gated the effect of time dependence. If we clear Eq. (9) of the diffusion term, neutral loss term and the volume recombination term, it almost coincides with our previous neutral model Eq. (7) except for the time derivative term. In a steady state, the neutral profile in the new model gave close agreement with that in our previous model.

Second, we compared the neutral decay length for convection-dominant case, $(\alpha,\beta) = (1, 0)$ with that for diffusion-dominant case, $(\alpha,\beta) = (0, 1)$ without the cross-field neutral loss term in attached regime. Figure 2 (a) shows that the neutral decay length becomes longer in the diffusion-dominant model. This was caused by the acceleration of the neutral particles by the charge exchange reaction.

Third, we compared the neutral profile with the cross-field neutral loss term with that without it. The time constant of the neutral loss term τ_n was set to be 10^{-4} s so that it is comparable to the time constants of other terms. Figure 2 (b) shows that the neutral density decreases in the high density region near the divertor plate with the cross-field neutral loss term.

3.2 Simulation of the detached regime

In the following results, we considered only diffusion process in the neutral flux by setting $(\alpha,\beta) = (0, 1)$. In order to simulate the detached plasma regime, we made the recycling rate η_{trap} higher. The time variation of spatial profiles of the plasma parameters are shown in Fig. 3. Here, the neutral loss term is not included and η_{trap} is set to be 95.4%. The detachment front reaches the X-point in a few milliseconds. The divertor density becomes about 2 orders lower than the peak density. The divertor temperature becomes much lower than 1 eV. The neutral does not decay because of the very low temperature in the detached region.

The flows of particles and heat in the detached regime are also investigated. Figure 4 shows the spatial (a) particle and (b) heat flux profile for t = 0.69 ms. The particle flux increases by the flux from the core plasma and ionization reaction. Near the detachment front, because of the adequately low temperature, the volume recombination dominates the ionization so that the particle flux decreases. The heat flux increases by the flux from the core in upstream region, however, after the sum of ionization, impurity radiation and charge exchange energy loss dominate it at x = 16.8, the heat flux starts to decrease gradually. At x = 20.1, the temperature becomes lower than 5.25 eV and the volume recombination reaction changes into heat source. Near the detachment front, the ionization and impurity radiation energy loss rapidly decrease, but charge exchange energy loss remains. In the detached region, the charge exchange energy loss dominates the volume recombination energy source so that the heat flux decreases.

In these simulations of detached regime, steady state has not been yet achieved, so that the detachment fronts move upstream beyond the X-point. If we introduce the cross-field heat transport, we might be able to make the detachment front more stable [6–8].

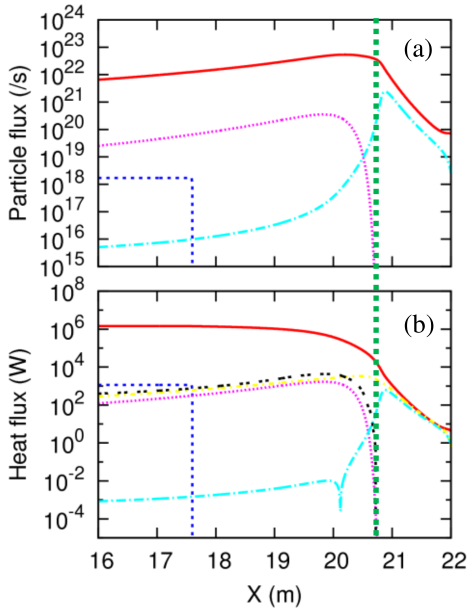

Fig. 4 Spatial (a) particle and (b) heat flux profile. Red lines represent local particle and heat flux. Blue input from the core plasma, pink ionization, aqua (absolute) recombination, yellow charge exchange, black impurity radiation. Detachment front is denoted by the vertical broken green line.

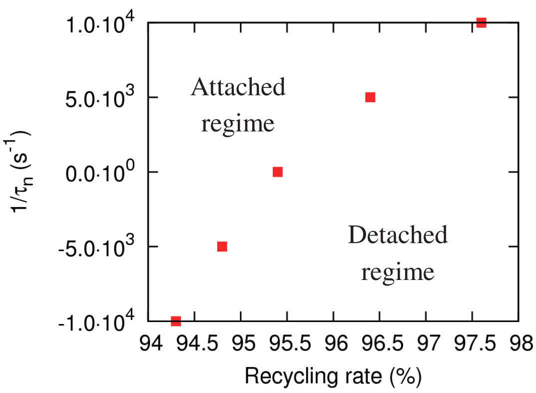

Fig. 5 Conditions of recycling rate and cross-field neutral loss time constant for detached regime to occur.

We also investigated the conditions of the recycling rate $\eta_{\rm trap}$ and cross-field neutral loss time constant $\tau_{\rm n}$ where the detached regime occurred. The conditions are shown in Fig. 5. If we set $\tau_{\rm n}$ to be negative value, the third term in the right hand side of Eq. (9) changes from loss term into source term, so that less recycling rate is needed for the detached regime to occur. It implies that, in multi-layer analyses, PDD plasmas might be reproduced by setting conditions of the cross-field neutral transport. This is also our future work.

4. Conclusion

In the one-dimensional SOL-divertor model, a self-consistent neutral model has been introduced. Detached divertor plasmas have been successfully reproduced and the flows of particles and heat from the core were investigated in single tube analyses. The conditions of recycling rate and time constant of cross-field neutral loss term for the detached regime to occur were also presented.

Current neutral model doesn't consider that the velocity of neutrals produced by volume recombination is affected by the velocity of original plasma particles and that neutrals are reflected at the divertor plate. Also neutrals should be divided into two or more generations according to whether they have experienced the charge exchange reaction or not. Such improvements are our future works.

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