1D Model Study on the Effect of Impurity Radiation Cooling in LHD SOL Plasma*)

Gakushi KAWAMURA, Izumi MURAKAMI, Yukihiro TOMITA and Suguru MASUZAKI

National Institute for Fusion Science, 322-6 Oroshi-cho Toki, Gifu 509-5292, Japan

(Received 11 December 2011 / Accepted 25 June 2012)

Increasing heat load to plasma-facing walls in future fusion devices and reactors could exceed the engineering limit of the material if simple scaling is applied in size of device to realize sufficient energy confinement time. One of possible means to remove the heat in plasma is impurity gas puffing. In order to investigate the plasma response to the radiation cooling, a one dimensional steady-state two-fluid model has been developed to describe SOL plasma of LHD. Model equations were solved numerically for various neon density and three types of SOL plasma. Maximum neon density above which plasma does not sustain is found. Significant reduction of temperature and heat flux onto the divertor plate are found. It is confirmed that the neon gas puffing is an effective technique to reduce the heat load onto divertor plates.

Keywords: radiation, impurity, SOL, divertor, LHD

DOI: 10.1585/pfr.7.2403129

1. Introduction

Recent progress in fusion plasma performance gives us perspectives on future fusion devices like DEMO and helical-type reactor, FFHR [1]. Increasing heat load onto plasma-facing walls in these devices, however, could exceed the engineering limit of material if simple scaling is applied in size of device to realize sufficient energy confinement time. The larger the device becomes, the more severe heat flux the wall has to sustain. One of possible means to remove the heat is gas puffing of impurity such as neon and nitrogen.

The cooling effect of impurity radiation introduced by the gas puffing has been demonstrated in the 14th experimental campaign of LHD in 2010 to 2011. It is found that the temperature and heat flux onto divertor plates is reduced significantly. Excess amount of gas puffing, however, causes radiation collapse. Low-density discharge can allow large amount of gas puffing and yields large radiation cooling. The physical understanding of the plasma response is desirable to apply the gas puffing to future operations. A one dimensional model along magnetic field line is a reasonable and useful tool to investigate simplified system by parameter surveys.

2. Fluid Modeling of SOL

We developed a one dimensional steady-state two-fluid model based on our previous divertor plasma model [2, 3] to study the cooling effect of gas-puffed neon on the hydrogen SOL plasma. In LHD magnetic field lines in the edge of the ergodic region are much shorter than those inside the ergodic region. They attach the divertor plate after a few toroidal turns and can be described in one dimensional model like tokamak SOL. We show the modeled geometry in Fig. 1. Diffusive transport exists from high- to low-density flux tubes and their difference deposits in the tube. The connection length is defined as $2L$. Recycling of hydrogen takes place in front of the divertor plates.

In the experiment, sustaining radiation in edge region outside the LCFS (last closed flux surface) is observed for several seconds after an instantaneous neon gas puffing. Since the characteristic time of atomic processes and increase of radiation take place is order of millisecond [4] and the transport time scale is also shorter than one second, we can safely assume that the neon distribution is in steady state. It also implies that the neon flux exists on the divertor plate and recycles continuously. Therefore, we apply a steady state plasma in the model. The radiation cooling is modeled as a loss term in the balance equation of energy flux. Another role of the impurity as a plasma source is ignored under the assumption of small amount of impurity,

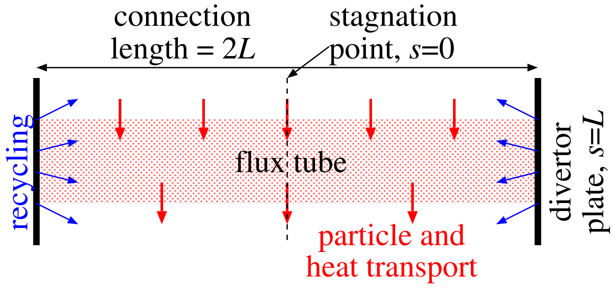

Fig. 1 Schematic view of 1D SOL model.

author's e-mail: kawamura.gakushi@nifs.ac.jp

*) This article is based on the presentation at the 21st International Toki Conference (ITC21).

i.e. a few percents at most.

We modeled the SOL plasma along a magnetic field line as steady state Braginskii equations;

$$\frac{\mathrm{d}G}{\mathrm{d}s} = S_{\mathrm{pt}} + S_{\mathrm{pn}}, \tag{1}$$

$$\frac{\mathrm{d}P}{\mathrm{d}s} = S_{\mathrm{mn}}, \tag{2}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}s} = S_{\mathrm{ht}} + S_{\mathrm{hn}} + S_{\mathrm{hr}}, \tag{3}$$

$$\frac{\mathrm{d}G_{\mathrm{n}}}{\mathrm{d}s} = -S_{\mathrm{pn}}. \tag{4}$$

The variable s represents field-aligned coordinate which has the origin at the stagnation point. The hydrogen ion flux, pressure, heat flux and neutral particle flux are, respectively, given by

$$G = nv, \tag{5}$$

$$P = mnv^2 + 2nT, \tag{6}$$

$$Q = \frac{1}{2}mnv^3 + 5nvT - \kappa_0 T^{5/2}\frac{\mathrm{d}T}{\mathrm{d}s}, \tag{7}$$

$$G_{\mathrm{n}} = n_{\mathrm{n}} v_{\mathrm{n}}, \tag{8}$$

where neutral and plasma densities, flow velocity, temperature, ion mass, heat conduction coefficient are denoted by n_{n}, n, v, T, m and $\kappa_0 T^{5/2}$, respectively. The velocity of hydrogen atom is denoted by v_{n} and assumed to be a constant determined by Frank-Condon process. The electron and ion temperatures are assumed to be the same. The source terms with subscript ‘n’, ‘t’ and ‘r’ represents plasma-neutral interaction, cross-field transport and radiation processes, respectively. They are modeled by

$$S_{\mathrm{pn}} = \langle\sigma v\rangle_{\mathrm{iz}} n_{\mathrm{n}} n, \tag{9}$$

$$S_{\mathrm{mn}} = -\langle\sigma v\rangle_{\mathrm{cx}} n_{\mathrm{n}} n v, \tag{10}$$

$$S_{\mathrm{hn}} = -32.75^{[\mathrm{eV}]}\langle\sigma v\rangle_{\mathrm{iz}} n_{\mathrm{n}} n - \left(\frac{1}{2}mv^2 + \frac{3}{2}T\right)\langle\sigma v\rangle_{\mathrm{cx}} n_{\mathrm{n}} n, \tag{11}$$

$$S_{\mathrm{pt}} = D\frac{\mathrm{d}^2 n}{\mathrm{d}r^2}, \tag{12}$$

$$S_{\mathrm{ht}} = \chi\frac{\mathrm{d}^2 nT}{\mathrm{d}r^2}, \tag{13}$$

$$S_{\mathrm{hr}} = -\langle\sigma v\rangle_{\mathrm{rad}} n_{\mathrm{imp}} n, \tag{14}$$

where rate coefficients of ionization and charge exchange are denoted by $\langle\sigma v\rangle_{\mathrm{iz}}$ and $\langle\sigma v\rangle_{\mathrm{cx}}$. The density of impurity, n_{imp}, is assumed to be constant and uniform in space. The radiation coefficient of impurity, $\langle\sigma v\rangle_{\mathrm{rad}}$ is calculated based on ADAS database [5] under the assumption of ionization equilibrium. Particle diffusion coefficient and heat transport coefficient are denoted by D and χ, respectively, and assumed to be constant. The energy loss, i.e. 32.75 [eV], by plasma-neutral interaction involves ionization energy, radiation by excitation and dissociation energy of a hydrogen molecule. The profile in the cross-field direction is simply modeled by decay length of density and temperature, λ_{n} and λ_{T} and then the source terms are calculated as $S_{\mathrm{pt}} = Dn/\lambda_{\mathrm{n}}^2$ and $S_{\mathrm{ht}} = \chi nT\,(1/\lambda_{\mathrm{n}} + 1/\lambda_{\mathrm{T}})^{-2}$.

We solve the Eqs. (1)–(4) numerically by integrating them from $s = L$ to $s = 0$ with 4th order Runge-Kutta method. Shooting method is employed to find a solution satisfying the boundary conditions,

$$v(0) = 0, \tag{15}$$

$$v(L) = \sqrt{\frac{2T}{m}}, \tag{16}$$

$$Q(0) = 0, \tag{17}$$

$$Q(L) = \frac{1}{2}n(L)v(L)T(L)\left(\ln\frac{m}{4\pi m_{\mathrm{e}}} + 11\right), \tag{18}$$

$$n_{\mathrm{n}}(L)v_{\mathrm{n}} = \alpha n(L)v(L). \tag{19}$$

The recycling coefficient of hydrogen is denoted by α and fixed to 1/4 in this paper. The particle and heat fluxes are zero at the stagnation point, $s = 0$, and limited [6] by the sheath at the sheath entrance, $s = L$. The decay lengths of density and temperature are assumed to be the same, i.e. $\lambda_{\mathrm{n}} = \lambda_{\mathrm{T}}$. By using the method mentioned above, the calculation time is much shorter than a second.

3. Results and Discussions

We carried out calculations for three conditions and the parameters used here are summarized in Table 1. The case 1 and 2 give low and high density plasma and the case 2 and 3 give long and short connection lengths. We note that the input power is a local quantity and different from the heating power of the device. The power transported to the flux tube by cross field diffusion is determined by the transport coefficient, decay length and spatial profiles of density and temperature. The coefficient D and χ are fixed and the decay lengths, $\lambda_{\mathrm{n}} = \lambda_{\mathrm{T}} \sim 5$ cm, are automatically adjusted by the shooting method. The density and temperature on the divertor plate listed in Table 2 are chosen by adjusting the power and transport coefficients manually.

Spatial profiles of density, velocity and temperature are shown in Fig. 2 for the cases 1 and 2. The low density condition, i.e. case 1, gives higher temperature compared

Table 1 Calculation parameter for three cases: Connection length, i.e. $2L$, transport coefficients and input power into the flux tube.

case	L	D	χ	input power
1	50 m	1 m^2/s	2.63 m^2/s	1.5 MW/m^2
2	50 m	1 m^2/s	1.9 m^2/s	5 MW/m^2
3	25 m	1 m^2/s	2.1 m^2/s	5 MW/m^2

Table 2 Density and temperature on the divertor plasma. The parameters listed in Table 1 were determined to give these quantities.

case	n_{div}	T_{div}
1	$\sim 3 \times 10^{17}$ m^{-3}	~ 45 eV
2	$\sim 4 \times 10^{18}$ m^{-3}	~ 17 eV
3	$\sim 4 \times 10^{18}$ m^{-3}	~ 16 eV

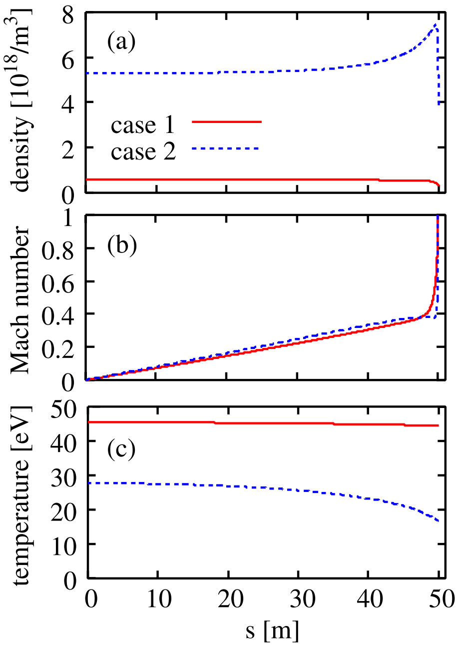

Fig. 2 Spatial profiles of density, velocity and temperature for cases 1 and 2.

with the high density condition, i.e. case 2. The profiles of the Mach number for the two cases are similar. The high density plasma has large density increase and temperature decrease toward the divertor plate except a narrow region in front of the divertor plates. This behavior is caused by the heat conduction in low temperature condition and discussed in detail in our previous work [2].

The neutral particles recycled from the divertor plate are ionized easily and localized in a narrow region, i.e. around one meter in front of the divertor plates. The sharp decrease of the density and increase of the velocity are caused by the plasma-neutral interaction. The change of the density and velocity in the collisional presheath can be estimated by integrating the balance equations of flux and pressure, i.e. Eqs. (1) and (2), from the entrance of the collisional presheath (CPS) to the entrance of the Debye sheath (DS) under the assumption of constant temperature; $n_{\mathrm{CPS}}/n_{\mathrm{DS}} = 1 + \sqrt{1-(1-\alpha)^2} \simeq 1.7$, $v_{\mathrm{CPS}}/v_{\mathrm{DS}} = (1-\alpha)/\left[1+\sqrt{1-(1-\alpha)^2}\right] \simeq 0.45$ for the recycling coefficient $\alpha = 1/4$. These ratios agree well with the results in Fig. 2 and thus, the calculation is numerically valid. The mean-free-path of neutral particles in ionization is the same order of the width of the leg plasma [3]. That implies the recycling coefficient, i.e. the fraction of ionized hydrogen to the atoms generated by the surface recombination, can be safely assumed to be lower than a half. Since the effect of the coefficient to the qualitative results is not essential under that assumption, we assumed $\alpha = 1/4$ in this work.

We assumed a uniform density distribution of neon and carried out parameter scans of the neon density. Large impurity density implies large amount of gas puffing.

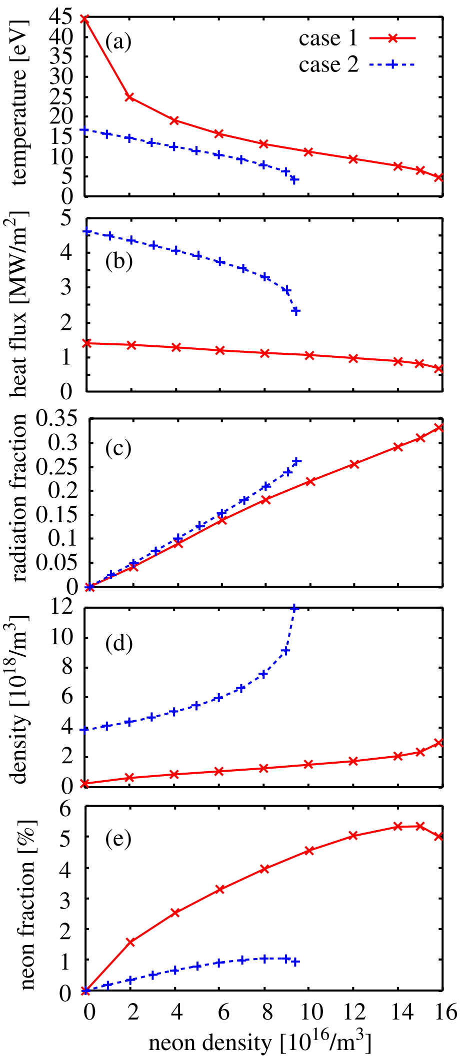

Fig. 3 Plasma response to the neon impurity. Temperature, heat flux, radiation fraction to input power, density and neon fraction at the divertor plates.

Since we assume constant input power independent of other plasma parameters, the radiation of neon leads to reduction of heat load. Figures 3 (a) and (b) show significant reduction of temperature and heat load onto the divertor plate according to the neon density. Figure 3 (c) shows the fraction of radiation power to the input power. They increase linearly to the neon density and reach one third approximately. There is a threshold above which a stable solution satisfying the boundary conditions, Eqs. (15)–(19), is not found. The low density condition, i.e. case 1, sustains for large amount of neon. All these tendencies of plasma response are consistent with the experimental observations described in Sec. 1.

Figure 3 (d) shows density on the divertor plates. They increase according to the neon density because the pressure is not so sensitive to the impurity and therefore low temperature leads to high density. The neon fraction shown in Fig. 3 (e) increases according to the neon density but turns to decrease when the neon density approaches the thresh-

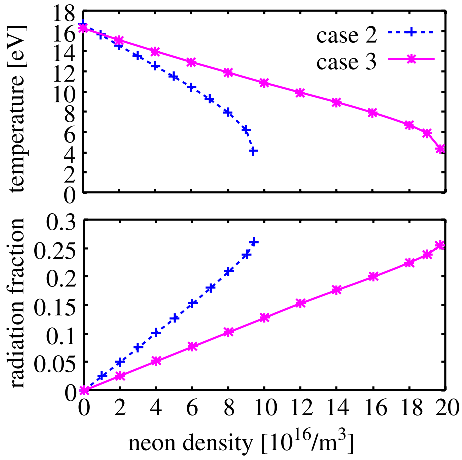

Fig. 4 Response of temperature and radiation fraction to input power at the divertor plate to the neon density.

old because of the steep increase of the plasma density. Experiment gives increase of the density due to neon gas puffing in the case of low density but decrease in the case of high density. Perpendicular particle transport is one of possible reasons of the discrepancy in the density response. The present model assumes the same decay length for density and temperature, i.e. $\lambda_n = \lambda_T$, and the length increases according to the neon density to satisfy the boundary conditions. The heat input is fixed in this work, but particle input depends on the particle flux onto the divertor plates. That implies change of particle input according to the impurity density. We carried out another set of calculation for the same parameter with constant input particle flux. The density, however, still increases slightly for large neon density. The recycling coefficient might be another reason. Although the recycling coefficient is assumed to be constant, it depends on plasma parameter and might change the transport. Investigation of the modeling of hydrogen recycling and perpendicular transport is necessary to understand the density response.

Comparisons between long, 200 m, and short, 100 m, connection lengths, i.e. case 2 and 3, are shown in Fig. 4. The total input power is the same and the plasma density and temperature of case 3 are adjusted to be the same as those of case 2. Since the total radiation power determines the plasma response, the plasma with a half connection length requires two times larger neon density to obtain the same temperature reduction.

4. Conclusions

We developed a one dimensional steady-state two-fluid model with radiation cooling by impurity. This model gives spatial profiles of density, velocity, temperature, heat flux and neutral density along a magnetic field line with specific connection length. We carried out parameter scans of the gas-puffed neon density under assumptions of constant power input and the same decay length of density and temperature of the hydrogen plasma. We choose three cases; low density with long connection length, high density with long connection length and high density with short connection length as listed in Table 1. The plasma response to the radiation cooling was investigated and we found the followings:

- There is a maximum threshold of neon density introduced by gas puffing. It lies around 1% of plasma density in the case 1 and 5% in the case 2. The low density plasma sustains for large amount of neon.
- Strong radiation of neon takes place and leads to significant reduction of temperature and heat flux onto the divertor plates. Larger radiation fraction to the input power is realized in lower density plasma.
- Plasma density increases according to the neon density because of decrease of the temperature. Steep increase are observed when the neon density approaches the threshold.
- Flux tube with short connection length requires large amount of neon density to obtain the same cooling effects.

The first and second findings are consistent with experimental results but the third is different. The probe measurement shows increase of the density in the case of low density and decrease in the case of high density. The discrepancy might occur due to the perpendicular transport and recycling coefficient, which can be affected by the impurity cooling. Further investigation is necessary on these issues.

The significant reduction of heat flux is a quite preferable for design of divertor material and cooling system. The large reduction of plasma temperature shown here is expected to prevent erosion significantly. Therefore we can conclude that the neon gas puffing is useful technique to protect the divertor plates. Although the model assumes the same temperature for electron and ion, the radiation power is taken from electron through the collision with impurity. The transport of heat and equilibrium of electron and ion temperature can be important to evaluate the material erosion. The spatial structure of plasma is another important point associated with the perpendicular transport. Benchmarking with experiment is necessary for more quantitative investigation.

[1] A. Sagara *et al.*, Fusion Eng. Des. **83**, 1690 (2008).
[2] G. Kawamura, Y. Tomita, M. Kobayasahi and D. Tskhakaya, J. Plasma Fusion Res. Series **8**, 455 (2009).
[3] G. Kawamura, Y. Tomita, M. Kobayasahi and D. Tskhakaya, Plasma Fusion Res. **5**, S1020 (2010).
[4] I. Murakami, D. Kato, H.A. Sakaue and S Masuzaki, Plasma Fusion Res. **6**, 2403029 (2011).
[5] H.P. Summers, The ADAS User Manual, version 2.6, http://www.adas.ac.uk/ (2004).
[6] P.C. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices* (Institute of Physics Publishing, Bristol and Philadelphia, 1999).