Analysis of Radiative Mantle Formation by Impurity Seeding in ITER

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In order to reduce high heat load on divertor plate in fusion reactors, we investigated radiative mantle formation scenarios by impurity seeding into scrape off layer (SOL) in ITER using the TOTAL simulation code. The low-Z impurity, like He, could not form a radiative mantle and have almost no contribution to the reduction of divertor heat load. On the contrary, the medium-Z impurity, like Kr, can form radiative mantle definitely and can radiate about 84% (core:33% / mantle:51%) of input power inside the last closed flux surface (LCFS) without any serious changes in density and temperature profile, and without inducing back transition from H to L mode. It can reduce divertor heat load about 60% compared with the case of no impurity injection in ITER.

Keywords: impurity, transport, radiative mantle, divertor, ITER

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1. Introduction

Unacceptably large power flux exhausted to the divertor region is one of the most serious issues in ITER. In particular, for future fusion reactors, heat loads on divertor plates are predicted to be very large, and therefore, plasma facing component materials would not tolerate their heat load.

To this problem, two different methods reducing heat load on divertor plates have been proposed. One is the solution called ‘radiative divertor’, and the other is ‘radiative mantle’.

In former solution, impurities are seeded into divertor chamber, and corresponding radiation enhancement is occurred inside the divertor region. On the other hand, in the latter one, impurities are seeded into scrape off layer (SOL) and convert the high energy flux into line radiation near the plasma edge which can scatter over the wider surface area of the first wall and divertor chamber.

If the radiative mantle formation could be maintained without inducing any harmful effects, it would be a beneficial solution to heat load problem in the next generation reactor.

In this analysis, we investigated radiative mantle formation by impurity seeding in ITER device. The radial distribution of impurity ions is calculated by using a 1.5-dimensional (1.5-D) toroidal transport analysis linkage code (TOTAL) [1]. In Section 2, the simulation code used in this paper is described. In Section 3, simulation results are presented, and a summary and discussions are presented in Section 4.

2. Numerical Model

2.1 Transport model

To investigate transport of fuel and impurity ions in a tokamak, we used a 1.5-D (1-D transport/2-D equilibrium for tokamak) time-dependent simulation model with low-Z gas and high-Z metal impurity dynamics. The plasma density \( n_e \), \( n_i \) and temperature \( T_e \), \( T_i \) are described as follows.

\[
\frac{\partial n_e}{\partial t} + \frac{1}{V'} \frac{\partial}{\partial p} V' T_e = S_p,
\]

\[
\sum_i z_i n_i = n_e,
\]

\[
\frac{3 \partial n_e T_e}{\partial t} + \frac{1}{V} \frac{\partial}{\partial p} \left( V' \left( q_e + \frac{5}{2} \Gamma_e T_e \right) \right) = P_{He} - P_{ei} - P_{rad} - \frac{1}{2} \Gamma_e E_r,
\]

\[
\frac{3 \partial n_i T_i}{\partial t} + \frac{1}{V} \frac{\partial}{\partial p} \left( V' \left( q_i + \frac{5}{2} \Gamma_i T_i \right) \right) = P_{He} - P_{ei} - P_{cx} - z_i \Gamma_i E_r,
\]

where \( q_e \) and \( q_i \) are electron and ion thermal energy fluxes, \( P_{He} \) and \( P_{ei} \) are additional electron and ion heating powers, \( P_{ei} \) is equi-partition power, \( P_{rad} \) and \( P_{cx} \) are radiation and charge-exchange loss powers, respectively. Here, \( \rho \) is the normalized radius, \( V \) is the volume defined by the equilibrium magnetic surface and its derivative is defined by \( V' = dV/dp \). The radiation loss \( P_{rad} \) is the sum of bremsstrahlung radiation, impurity line radiation, and synchrotron radiation powers.

For the anomalous part of the transport coefficients, the scaling model is used in this paper.

\[
\chi_{ano} = \chi_0 (t) \left( 1 + A \rho^p \right),
\]

\[
\chi_0 (t) = \chi_0 (t - \Delta t) + \Delta t \left( \tau_e^{PLA} T_E^{SC} - 1 \right).
\]
A simple parabolic profile ($\mu = 2$) and $\lambda \equiv \chi_0/\chi_0 - 1 = 1$ model is assumed for the thermal transport coefficient. Here, $\tau_{e, pl}$ is global energy confinement time calculated from the global plasma energy and the total heating power. For the scaling global confinement time $\tau_{e, SC}^{ ITER-P}$, we use the following L- and H-mode scaling laws,

$$\tau_{e, SC}^{ITER-P} (s) = 0.048 B_P^{0.85} R_0^{1.2} \times d^{0.3} n_2^{-0.1} B_1^{-0.2} (A_k n_e/P_0)^{0.15},$$

$$\tau_{e, SC}^{IPB98/92} (s) = 0.0562 B_0^{0.98} B_1^{1.15} \times P^{-0.09} M_i^{0.19} R_1^{1.97} n_{e, c}^{-0.41} \epsilon^{-0.58} k^{0.87}.$$

Using this model, we can simulate most probable plasma confinement derived from various experimental machines.

### 2.2 Impurity model

We examined impurities with a model for impurities in TOTAL; the multi-species dynamic impurity code IMPDYN [3] was used to model the ionization states, and the NCLASS code [4] was used for the full neoclassical transport of each charge state considering arbitrary aspect ratio and collisionality.

For the impurity dynamics [5, 6], the rate equation and diffusion equation are solved using the IMPDYN code [3] coupled with the ADPAK atomic physics package [7], which can calculate the cooling rate,

$$\frac{dn_k}{dt} = -\frac{1}{V_p} \frac{\partial}{\partial n_k} \left( \frac{V_p}{\partial n_k} \right) + \gamma_{k-1} n_{k-1} - \left( \alpha_{k+1} + \gamma_k \right) n_k + S_k,$$

$$\Gamma_k = \Gamma_k^{NCs} + \Gamma_k^{NCa} - D_k (\partial n_k / \partial \rho) + V_k (\partial n_k / \partial \rho).$$

with ionization rate $\gamma_k$, recombination rate $\alpha_k$, and impurity source term $S_k$. Here a constant anomalous diffusion coefficient $D_k$ and simply modeled inward velocity $V_k = V(a)/(a/a)$ are used for impurity anomalous transport ($V_k < 0$ corresponds to inward velocity). The main fuel neutrals are calculated by the AURORA Monte Carlo code [8].

The neoclassical impurity flux in a tokamak is expressed by

$$\Gamma_k^{NCs} = -D_k^{NC} \nabla n_k + D_k^{NC} \sum \left( g_{at-k} \nabla n_{i} / n_i \right)$$

$$+ g_{r1} \nabla T_1 / T_1 + g_{r2} \nabla T_2 / T_2.$$

In the simulation, the impurity source was defined as the impurity neutral flux on the plasma boundary. The neutral impurity density profile $n_0 (\rho)$ is assumed to be

$$n_0 (\rho) = \frac{V_p (1) \Gamma_0 (1)}{V_p (\rho) v_0} \exp \left[ -\frac{1}{V_p (\rho) v_0} \int_{0, \rho_1} \rho \phi_m (\rho) \gamma_0 (\rho, \rho) d\rho \right].$$

Here, $\Gamma_0 (1)$ is the neutral impurity flux at the plasma boundary ($\rho = 1$), and $\gamma_0 (\rho)$ is the neutral impurity inward velocity (assuming an energy of 10 eV). The symbols $v_0$ and $n_0$ are the ionization coefficient and electron density near the plasma boundary, respectively.

To clarify the effect of impurity ions, steady-state burning plasma conditions were established without impurities. Then, a continuous neutral impurity influx was introduced, and after a transient phase, the system settled into a new radiation-enhanced steady state.

### 2.3 Divertor model

In this analysis, two point model based on Borrass model [9] is coupled to the TOTAL code.

$$n_D = \frac{f_p}{1 + M_D^2 T_D},$$

$$\Delta = \frac{5}{32} \frac{c n_s T_2^4 F}{q_1 B_0},$$

$$T_S = \left( \frac{49 q_1 L^2}{\Delta} \right)^{2/7},$$

$$\frac{\gamma L (1 - f_{imp}) q_\perp}{2 \Delta} = c_n n_D M_D \left[ \phi + (\gamma + M_D^2 T_D) T_D \right].$$

Here, subscripts S and D represent stagnation point and divertor quantities, respectively. $L$ is the connection length and $q_\perp$ is the mean power flux across the separatrix. $M_D$ is the Mach number at the target. The coefficient $f_p$ is the drop of total pressure (static and kinetic by momentum loss due to ion-neutral collisions) in the divertor region and we use $f_p = 2$ as an input parameter in this simulation. The coefficient $f_{imp}$ is the impurity radiative fraction in the SOL region and is assumed $f_{imp} = 0$ in this analysis. Therefore we did not include the impurity radiation in the SOL region.

### 3. Simulation Results

#### 3.1 Maximum impurity concentration

We investigated radiative mantle formation in ITER for low-Z impurity (He, C, O, Ne) and medium-Z impurity (Ar, Fe, Kr, Mo). To clarify the maximum impurity concentration at the reference ITER inductive scenario based on the ELMMy H-mode regime, we use the following three constraints.

$$P_a^L - P_a^R \leq P_a^L \cdot 5\%,$$

$$P_{fus} \geq 10 P_{RF},$$

$$P_{sep} \geq P_{H-L}.$$
Table 1 Related parameters for various impurity species at maximum concentration.

<table>
<thead>
<tr>
<th></th>
<th>No imp</th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{imp}} \text{[%]}$</td>
<td>0</td>
<td>11.54</td>
<td>0.9729</td>
<td>0.1707</td>
<td>0.0166</td>
</tr>
<tr>
<td>$P_{\text{rad}} \text{[MW]}$</td>
<td>26.75</td>
<td>66.35</td>
<td>105.7</td>
<td>115.92</td>
<td>132.51</td>
</tr>
<tr>
<td>$P_{\text{sep}} \text{[MW]}$</td>
<td>130</td>
<td>85.94</td>
<td>51.11</td>
<td>41.79</td>
<td>25.87</td>
</tr>
<tr>
<td>$P_{\text{II-L}} \text{[MW]}$</td>
<td>25.08</td>
<td>85.94</td>
<td>27.66</td>
<td>25.82</td>
<td>25.04</td>
</tr>
<tr>
<td>$T_{\text{ne}} \text{[eV]}$</td>
<td>185.31</td>
<td>149.1</td>
<td>132.91</td>
<td>126.12</td>
<td>111.85</td>
</tr>
</tbody>
</table>

3.2 Impurity dependence of radiation fraction

Figure 2 shows the radiation fraction dependence on impurity concentration for the case of injecting He, Ne, Ar and Kr. Here, we define the region between $q = 2$ surface and LCFS as plasma mantle region, and assume the region inside the $q = 2$ surface as plasma core region. In the case of He injection, the ratio of radiation from the core increases rather than those from the mantle region as impurity concentration increases. On the contrary, in Kr injection case, the ratio of the mantle radiation to the total radiation exceeds that of the core radiation at about Kr concentration of 0.008% with respect to electron density. As shown in the figure, Kr impurity can form radiative mantle definitely, and radiate about 51% of input power from the mantle, and 33% from the core.

3.3 Total exhausted radiation

The ratio of each radiation process (bremsstrahlung radiation, impurity line radiation, and synchrotron radiation) on total radiation is summarized on bar chart in Figure 3. The injected Kr impurity is the most radiative by the line radiation near the plasma edge, and the impurity density is rather small, which is keeping bremsstrahlung radiation loss to the lower level. In the case of He impurity, injected impurity is almost all ionized in the core, even near the edge, and the impurity density is several hundred times larger than that of Kr impurity case. Therefore, it induces the increase in effective-Z, and correspondingly causes large bremsstrahlung radiation loss rate.

3.4 The case of Kr injection

In previous subsections, we clarified that Kr impurity can form radiative mantle. Thus, we confirm whether any deleterious changes are induced after Kr impurity injection in this subsection.

The time history of global power quantities are shown in Figure 4. The Kr impurity injection is started at $t = 100$ sec, and simultaneously power flux across the separatrix $P_{\text{sep}}$ is reduced a lot. Through impurity injection, alpha heating power $P_{\text{alp}}$ is feedback controlled to keep 105 MW by fuel gas puffing. In Fig. 5, the contours of Kr impurity density and corresponding total radiation profile are shown. They represent that impurity radial profile and corresponding radiation mantle is settled to the steady state at 30 sec after starting of impurity injection.

Figure 6 shows the radial profiles of electron density, electron temperature and ion temperature before and after impurity injection. The electron density is increased and the temperature profile becomes slightly peaked through impurity injection. After impurity injection, the effective
4. Summary and Discussions

We investigated radiative mantle formation by impurity seeding in ITER and clarified the following results:

1. Low-Z impurity, like He, cannot form radiative mantle, and causes large bremsstrahlung radiation loss in the core.

2. About 84% (core:33%/mantle:51%) of input power is radiated inside the LCFS by Kr impurity seeding without inducing any deleterious change.

The deference between the radiative mantle formation by Kr and by He seems to come from the atomic processes including ionization, recombination and their relevant radiation processes. The impurity transport processes including inward flows are also generally important, but these effects on the difference might be small in the present parabolic transport coefficient model derived from the global confinement scaling law.

In this simulation, impurity transport in SOL/divertor region is not included and impurity influx is supposed at LCFS. In the case of low-Z impurity, almost all impurity atoms injected into the plasma periphery might be ionized in SOL. However, high-Z impurities such as tungsten impurities will penetrate into the core as partially ionized particles. That high-Z impurity penetration process was calculated in this simulation as shown in Ref. [6]. We should also consider the case of impurity pellet injection. The detailed dynamics of impurity neutrals including ionization and recombination requires 3-dimensional simulation, which is out of scope in the present research. The impurity total analysis from the core to the divertor region is needed, and we will discuss the relation between radiative mantle and ‘radiative divertor’ in the near future.