Journal of Nuclear Materials 463 (2015) 185–188

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Effects of impurity transport and melt layer motion to the tungsten wall erosion during anomaly events

K. Ibano *, T. Tsutsui, T.L. Lang, S. Togo, Y. Ogawa

Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Japan

ARTICLE INFO

Article history:
Available online 14 October 2014

ABSTRACT

Developing designs of future fusion devices, safety and soundness of the rector at anomaly events must be ensured. A computational approach is being taken by developing a homegrown integrated reactor simulation code and analyzing a loss-of-cooling-gas-puff accident (LCGA). This code currently includes simple plasma, edge, and wall models. In this study, models for the tungsten transport and melt layer motion was added and used for the analysis. It was found that this accident results significant erosion of the wall while impurities from the wall would contribute the radiation cooling for the intense heat flux. However, these effects strongly depend on an uncertain parameter of the tungsten transport as well as the tungsten melt layer motion. Thus, parametric survey for these uncertain quantities were taken and discussed.

1. Introduction

For the development of safe and robust fusion reactor designs, transient analyses of the reactor at normal and anomaly events are essential. Several studies are known for analyses on anomaly events such as the loss-of-coolant accident (LOCA) and the loss-of-plasma-control accident (LPCA) [1–5]. Most of the studies concluded that the impurity generation from walls and the transportation to the core plasma increase the radiation power which triggers a termination of the plasma. While this self-shutdown property confirms the inherent safety of fusion reactors, a significant erosion of the wall is expected before the termination.

As well as the LOCA and the LPCA, the authors concern about a loss-of-coolant-gas-puff accident (LCGA). At the LCGA, following sequential phenomena is expected. First, sudden loss of divertor impurity density leads decrease of radiation cooling and significant increase of concentrated heat flux at the strike point. Then, the higher flux leads higher impurity emission from walls which would increase the radiation power at the CORE. In the meantime, since the puffed impurity gas is decreasing at CORE, the inherent shutdown would happen slower than the LOCA and other anomaly events in which the seeded impurities still remain in the plasma. Thus, LCGA can be the most severe accident for the wall erosion.

For the analysis on the LCGA and other anomaly events, an integrated reactor simulation code named RAILS (*R*e*A*ctor *I*ntegrated simu*L*ation code for *S*afe fusion operation) is being developed by the authors. In this model, core, SOL, and divertor plasma as well as heat transfer and sputtering at the wall, mainly divertor, and interaction between them were calculated. Similar code have been developed and known as SAFALY [1,2] and AINA [3,4]. Main originality of RAILS code is an updated two-point model for the SOL and DIV plasmas. Basic features of RAILS were explained in Section 2.

In Section 3, results of analyses on the LCGA by RAILS are discussed. It was found that the final erosion amounts are dependent on several parameters such as time constants of impurity transport and melt layer motion. Therefore, parametric surveys were taken to study sensitivities of the parameters. Found sensitivities of the impurity transport time as well as the melt surface motion speed [6] to the erosion due to LCGA were shown and discussed.

2. Models

2.1. Core plasma model

The core plasma model consists of energy balance and particle balance equations of ions and electrons. The energy balance is expressed by

$$\frac{3}{2}\cdot\frac{\mathrm{d}}{\mathrm{d}t}(nT_\mathrm{i}) = f_{\alpha\mathrm{i}}P_\alpha + f_\mathrm{auxi}P_\mathrm{aux} - P_\mathrm{ie} - \frac{3}{2}\cdot\frac{nT_\mathrm{i}}{\tau_\mathrm{Ei}} \tag{1}$$

$$\frac{3}{2}\cdot\frac{\mathrm{d}}{\mathrm{d}t}(n_\mathrm{e}T_\mathrm{e}) = (1-f_{\alpha\mathrm{i}})P_\alpha + (1-f_\mathrm{auxi})P_\mathrm{aux} + P_\mathrm{ie} + P_\mathrm{oh} - P_\mathrm{Br} - P_\mathrm{sy} - P_\mathrm{line} - \frac{3}{2}\frac{n_\mathrm{e}T_\mathrm{e}}{\tau_\mathrm{Ee}} \tag{2}$$

---

* Corresponding author at: Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka, Japan.

E-mail addresses: kibano@eei.eng.osaka-u.ac.jp, kibano@gmail.com (K. Ibano).

http://dx.doi.org/10.1016/j.jnucmat.2014.09.082
0022-3115/

where n is density, T is temperature, $f_{\alpha i}$ is power fraction contributing to ion, P_{alpha} is heating power by fusion alpha particles, P_{aux} is heating power by auxiliary heating devices and assumed as a constant (50 MW), P_{ie} is exchange power between ions and electrons, τ_{E} is energy confinement time determined by $\mathrm{HH}^{(y,2)}$ scaling with a unity confinement improvement factor, P_{oh} is heating power by ohmic reactions, P_{Br} is cooling power by Bremmstraung radiation, P_{sy} is cooling power by synchrotron radiation, P_{line} is cooling power by impurity radiation, and index i, e and α indicate ion, electron and alpha particles, respectively.

The particle conservation is expressed by

$$\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathrm{i}} = S_{\mathrm{i}} - \frac{1}{2}f_{\mathrm{p}}n_{\mathrm{i}}^2\langle\sigma v\rangle_{\mathrm{DT}} - \frac{n_{\mathrm{i}}}{\tau_{\mathrm{pi}}} \tag{3}$$

where S_{i} is ion source, e.g. gas puffing, $\langle\sigma v\rangle_{\mathrm{DT}}$ is the cross section for the D–T fusion, f_{p} is a factor for the fusion reaction in order to include the temperature and density distribution effect at the core plasma. τ_{pi} is a particle confinement time for ions, and obtained by multiplying a given factor to the energy confinement time.

2.2. Scrape-off layer and divertor plasma model

For the scrape-off-layer (SOL) and divertor (DIV) plasma, the CSD model [7] was applied. This model is based on the two-point model, but the SOL density is obtained from the particle balance instead of using a scaling law.

It has to be mentioned that a sudden temperature and density changes due to the two point model and the strong nonlinearity of the radiation power of Argon occasionally give unstable conditions due to too much radiation. Thus, in the calculation, special attentions were paid for the impurity radiation loss ($f_{\mathrm{rad}}^{\mathrm{imp}}$) and the impurity pumping. First, the radiation fraction value was fixed at a given input value and the required cooling gas amount was determined. Then, once steady-state condition was achieved, the radiation fraction is determined from the impurity radiations. For the LCGA calculations, quick disappearances of impurity from the divertor plasma were assumed. These special treatments were taken so that the result becomes conservative. Update of the model into a 1-D MHD model will be quite helpful in order to avoid these special treatments.

Using the temperature and the density of SOL and DIV plasma obtained by the CSD model, radiation power of impurities were determined by

$$P = Lz_{(T_{\mathrm{e}})}n_{\mathrm{imp}}n_{\mathrm{e}} \tag{4}$$

where Lz is a radiation rate density obtained from Ref. [8]. These radiation power were calculated both at SOL and DIV plasma and used for the $f_{\mathrm{rad}}^{\mathrm{imp}}$ calculation.

2.3. Wall model

Temperature distribution of the wall to the depth direction was analyzed by a 1-D heat transfer equation as

$$\rho C_{\mathrm{p}}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa\frac{\partial T}{\partial x}\right) \tag{5}$$

where ρ, c_{p}, κ are density, heat capacity and thermal conductivity, respectively. Heat flux boundary condition at the plasma side and convective cooling boundary condition at the other side were assumed. Heat flux at the strike point was obtained from the CSD model with an assumed angle of 24.5° between the divertor tile and the magnetic line. Latent heat of melting was not taken into account in this analysis due to its limited effect while energetic cost of evaporation was taken into account at the surface boundary. For the cooling side, water coolant flow with temperature of 100 °C was assumed. Two layer models with 15 mm thick W and 3 mm thick Cu layers were assumed. No thermal resistivity was assumed at the interface of W and Cu.

2.4. Impurity transport model

Transport of generated or induced impurities between divertor, SOL, and core plasma regions were analyzed by a simple model as follows;

$$\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathrm{imp}}^{\mathrm{CORE}} = \frac{n_{\mathrm{imp}}^{\mathrm{SOL}}}{\tau_{\mathrm{imp}\perp}^{\mathrm{SOL}}} - \frac{n_{\mathrm{imp}}^{\mathrm{CORE}}}{\tau_{\mathrm{imp}\perp}^{\mathrm{CORE}}} \tag{6}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathrm{imp}}^{\mathrm{SOL}} = -\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathrm{imp}}^{\mathrm{CORE}} - \frac{1}{\tau_{\mathrm{imp}\|}^{\mathrm{SD}}}\left(n_{\mathrm{imp}}^{\mathrm{SOL}} - n_{\mathrm{imp}}^{\mathrm{DIV}}\right) \tag{7}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}n_{\mathrm{imp}}^{\mathrm{DIV}} = S_{\mathrm{puff/wall}} + \frac{1}{\tau_{\mathrm{imp}\|}^{\mathrm{SD}}}\left(n_{\mathrm{imp}}^{\mathrm{SOL}} - n_{\mathrm{imp}}^{\mathrm{DIV}}\right) - \frac{n_{\mathrm{imp}}^{\mathrm{DIV}}}{\tau_{\mathrm{pump}}} \tag{8}$$

where $\tau_{\mathrm{imp}\perp}^{\mathrm{SOL}}$, $\tau_{\mathrm{imp}\perp}^{\mathrm{CORE}}$, and $\tau_{\mathrm{imp}\|}^{\mathrm{SOL/DIV}}$ are delay time constants of impurity transport from SOL to CORE plasma, CORE to SOL plasma, and between SOL and DIV plasmas, respectively. $\tau_{\mathrm{imp}\perp}^{\mathrm{SOL}}$ and $\tau_{\mathrm{imp}\perp}^{\mathrm{CORE}}$ were separately defined so that the impact of each parameters due to different mechanisms can be studied explicitly. S_{puff} is an input impurity gas puff amount to the divertor, and τ_{pump} is a delay time constant for the pumping. Since there are large uncertainties on the impurity transport between SOL and CORE, $\tau_{\mathrm{imp}\perp}^{\mathrm{SOL}}$ was surveyed as discussed in 3.2. In this survey, $\tau_{\mathrm{imp}\perp}^{\mathrm{SOL}} > \tau_{\mathrm{imp}\perp}^{\mathrm{CORE}}$ describes an impurity isolation condition, and $\tau_{\mathrm{imp}\perp}^{\mathrm{SOL}} < \tau_{\mathrm{imp}\perp}^{\mathrm{CORE}}$ describes an impurity accumulation condition.

Source of wall impurities S_{wall} was calculated as

$$S_{\mathrm{wall}} = C_{\mathrm{escape}}\left(Y_{\mathrm{sput}}\Gamma_{\mathrm{ions}} + \frac{N_{\mathrm{Av}}\rho A_{\mathrm{DIV}}}{m_0}\alpha_0 C\frac{1}{\sqrt{T}}\exp\left(-\frac{\Delta H}{\kappa T}\right)\right) \tag{9}$$

where C_{escape} indicates ratio of escaped particles which do not promptly re-deposit back to the surface and assumed as 0.01–0.025%. These significantly small values should be chosen in order to avoid strong erosion during the stead-state operation and easy termination of the plasma due to the wall impurity. The smaller escape rate, the operation continues longer after the incident continues while the smaller erosion during the steady-state. Since the purpose of this study is to analyze the safety at anomaly events, a conservative assumption, the smaller escape rate, was taken. Similar assumptions are seen in [3]. Y_{sput} is the sputtering yield of tungsten. Effective sputtering yield values from [9] were used for Y_{sput}. Since uncertainties exist for Y_{sput} in particular at the low-energy region, the sensitivity of the sputtering models should be evaluated in future.

2.5. Melt layer motion model

Movement of melt layer was modeled using a time constant as

$$\frac{\mathrm{d}h}{\mathrm{d}t} = -\frac{\Delta_{\mathrm{melt}}}{\tau_{\mathrm{melt}}} \tag{10}$$

where h is a total thickness of the first wall, Δ_{melt} is a melt thickness with temperature above the melt point, and τ_{melt} is a time constant of the melt layer motion. This time constant indicates required time of melt layer to leave from the intense heat flux region to the neighbor where the heat flux is relatively low. Thus, this model does not include a difference between melt layer motion on the surface and the ejection of droplets.