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Development of an Integrated Safety Analysis Code with 1-D SOL/DIV Transport Models

１次元SOL/DIV輸送モデルを含めた統合安全解析コードの開発

Teelong Lang[1], Toshiki Tsutsui[1*], Satoshi Togo[1], Kenzo Ibano[2] and Yuichi Ogawa[1]
ランティーロン, 筒井俊樹, 東郷訓, 伊庭野健造, 小川雄一

[1]*Graduate School of Frontier Sciences, the University of Tokyo*
5-1-5 Kashiwanoha, Kashiwa, Chiba, Kashiwa Research Complex 277-8568, Japan
[1]東京大学大学院総合研究棟〒277-8568　千葉県柏市柏の葉5-1-5
[2]*Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan*
[2]大阪大学大学院工学研究科〒565-0871　大阪府吹田市山田丘2-1

An integrated reactor simulation code, RAILS with one dimensional (1-D) SOL/DIV transport models has been developed. Realistic SOL/DIV transport models are crucial for the development of the safety analysis code for fusion devices. Hence, by using the plasma conditions of the 1-D SOL/DIV transport model, an impurity transport model by considering the effects of the thermal and friction forces could be developed. Furthermore, a neutral particle model was integrated. By implementing these two models into the code, the effects on the plasma operation at various plasma conditions could be described more precisely.

1. Introduction

An integrated reactor simulation code, RAILS has been developed to evaluate the robustness of a fusion reactor. Several anomaly events inside the fusion reactor such as loss of cooling accident (LOCA), loss of cooling gas puff accident (LCGA), and loss of plasma control could potentially cause unwanted wall erosion, core dilution and other abnormal events which are beyond our prediction. Thus, it is necessary to develop a realistic simulation code to study various plasma behaviors inside a fusion reactor. The RAILS code is updated and used similar concepts from existing safety analysis codes: SAFALY [1] and AINA [2].

One of the critical issues in designing next generation fusion reactors is to reduce the heat load onto the divertor target. It is found that the detached plasma scheme is considered as a promising candidate in tackling the issue [3]. In order to achieve the stable detached or reduced heat flux condition, the understanding of impurity transport mechanism in SOL/DIV is indispensable.

With the development of RAILS, the interaction between fusion plasma and plasma facing components (PFCs) could be studied more precisely. Thus, the 1-D SOL/DIV plasma transport model was developed and integrated into the RAILS code.

2. Structure of RAILS

The main structure of RAILS consist of a 0-D core plasma model which is adapted from [1], 1-D SOL/DIV model which is adapted from [4], and the wall melting model which is discussed in [5]. The structure is described as shown in Fig. 1.

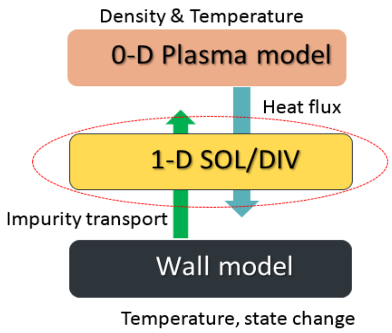

Fig. 1. Main structure of RAILS.

3. 1-D SOL/DIV Model

The 1-D plasma fluid transport model which is adapted from [4] is used to analyze the SOL/DIV plasma along the magnetic field line as shown in Fig. 2.

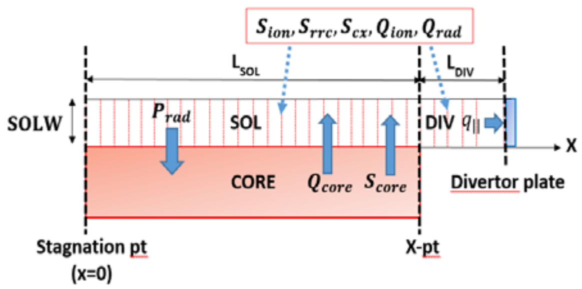

Fig. 2. Structure of 1-D SOL/DIV model in RAILS.

For simplicity, charge neutrality and ambipolar conditions were assumed whereby $n_i = n_e, V_i = V_e$, and $T_i = T_e$. The subscripts 'i' and 'e' denotes ion and electron respectively.

3.1 *Neutral particle model* [4]

$$\frac{\partial n_n}{\partial t} + \frac{\partial}{\partial s}\left(-D\frac{\partial n_n}{\partial s}\right) = -nn_n\langle\sigma v\rangle_{ion} + n^2\langle\sigma v\rangle_{rec} \quad (1)$$

$$D = \frac{T}{mn\langle\sigma v\rangle_{cex}}, ds = dx sin\theta \quad (2)$$

s is the length along the magnetic field line. θ is the angle at which the magnetic field line intersects the divertor plate. $\langle\sigma v\rangle_{ion}$, $\langle\sigma v\rangle_{rec}$ and $\langle\sigma v\rangle_{cex}$ are rate coefficients due to ionization, recombination and charge exchange processes respectively.

The following boundary condition is imposed at the divertor plate:

$$-D\frac{\partial n_n}{\partial z} = -\eta_{\mathrm{rcyl}} n_d V_d sin\theta \quad (3)$$

η_{rcyl} is the recycling rate and the subscript 'd' denotes divertor plate.

3.2 *Impurity model* [6, 7]

$$\frac{\partial}{\partial t}(m_Z n_Z V_Z) + \frac{\partial}{\partial x}(m_Z n_Z V_Z^2 + P_Z) - n_Z ZeE_{||} - n_Z m_Z (V - V_Z)/\tau_Z - 0.71 Z^2 n_Z \frac{\partial T_e}{\partial x} - 2.6 Z^2 n_Z \frac{\partial T_i}{\partial x} = M_Z \quad (4)$$

$$\frac{\partial n_Z}{\partial t} + \frac{\partial}{\partial x}(n_Z V_Z) = S_Z \quad (5)$$

The terms, $ZeE_{||}, \frac{m_Z(V-V_Z)}{\tau_Z}, -0.71Z^2 n_Z \frac{\partial T_e}{\partial x} - 2.6Z^2 n_Z \frac{\partial T_i}{\partial x}$ are the electrostatic force, frictional force and thermal forces due to electron and ion temperature gradients respectively. $E_{||}$ is given as below:

$$eE_{||} = -\frac{1}{n_e}\frac{\partial}{\partial x}(n_e T_e) - 0.71\frac{\partial}{\partial x}(T_e) \quad (6)$$

τ_Z is the impurity coulomb collision time [7] which is as shown below:

$$\tau_Z = \frac{1.47 \times 10^{13} m_Z T_i (T_i/m_i)^{1.5}}{(1 + m_i/m_Z) n_i Z^2 \ln\Lambda} \quad (7)$$

m_Z and m_i are Tungsten mass and plasma mass which are measured in atomic mass unit. $\ln\Lambda$ is the Coulomb logarithm.

M_Z and S_Z are the source terms for impurity momentum and continuity equations respectively. The source terms are given as follows:

$$M_Z = S_{Z-1} m_Z n_{Z-1} n_e V_{Z-1} - (S_Z + R_Z) m_Z n_Z n_e V_Z + R_{Z+1} m_Z n_{Z+1} n_e V_{Z+1} \quad (8)$$

$$S_Z = S_{Z-1} n_e n_{Z-1} - (S_Z + R_Z) n_e n_Z + R_Z n_e n_{Z+1} + d_Z \quad (9)$$

S_Z and R_Z are Tungsten rate coefficients for ionization and recombination processes at charge state, Z which used the fitting formulae from [8].

The total density due to plasma and impurity is given as:

$$n_e = n_{DT} + \sum_Z n_Z \quad (10)$$

n_{DT} is the plasma density.

The following boundary conditions are imposed:

$$V_Z(x = 0) = 0 \quad (11a)$$

$$V_Z(x = L) = \sqrt{T_Z/m_Z}, T_Z \approx T_i \quad (11b)$$

d_Z is the neutral Tungsten source (Z=0) at the divertor plate.

4. Discussions

Tungsten impurity transport mechanism by considering effects of thermal and friction forces and the background plasma from 1-D SOL/DIV model will be studied for charge state, Z=0 to 12 as higher charge state, Z=13 to 74 is not considered in this study as they form the core charge states [9].

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