Development of models for time-dependent integrated pedestal simulations

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Introduction

The confinement performance of H-mode plasmas depends strongly on the pressure profile in the pedestal region. EPED1 model [1] is a widely used pedestal model, which determines the pedestal height and width based on MHD stabilities and turbulence without considering energy fluxes. The pressure in the pedestal region of a type-I edge localized mode (ELM) H-mode plasma is dominated by transport, MHD instabilities and turbulence. Here, the pressure gradually increases in the transport timescale, and then it suddenly decreases when it reaches the upper limit constrained by MHD instabilities and turbulence. Therefore, we need to solve transport, evaluating whether the pressure remains below the stability limit at each time step. In this study, we propose an empirical transport model for the edge region, and construct a neural network (NN) based ideal MHD stability model. These models are introduced into a transport code and are used to perform transport simulations of H-mode plasmas with ELMs.

Empirical transport model for the edge region

A pedestal transport model that is widely used and reliable has not been established. One of the difficulties for the construction of pedestal transport models comes from the fact that various transport channels bring transport into the region. Our proposed model predicts transport coefficients using experimental observation. JT-60U experiments indicate that the loss of the stored energy due to the ELM normalized by the power crossing the separatrix P_{sep}, $f_{\mathrm{ELM}}\Delta W_{\mathrm{ELM}}/P_{\mathrm{sep}}$, is almost constant [2]. Here, f_{ELM} is the ELM frequency and ΔW_{ELM} is the drop in the stored energy at each ELM. The same tendency is found for a subset of unseeded deuterium JET-ILW plasmas with the plasma current

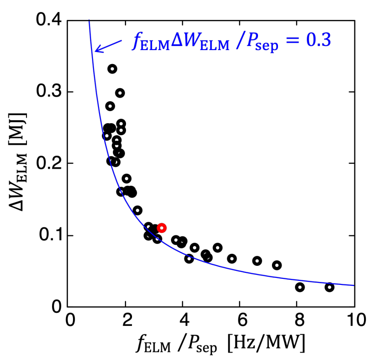

Figure 1. Dependence of ΔW_{ELM} on $f_{\mathrm{ELM}}\Delta W_{\mathrm{ELM}}/P_{\mathrm{sep}}$ for a subset of JET palsmas (#82035–82495). The red circle denotes #82435, the plasma for the simulations in this paper.

$I_\mathrm{p} = 2.0/2.5$ MA and the toroidal magnetic field $B_\mathrm{T} = 1.9-2.7$ T, as shown in Fig. 1. Based on the observation, we assume that $f_\mathrm{ELM}\Delta W_\mathrm{ELM}/P_\mathrm{sep}$ is a known value. f_ELM is also assumed to be estimated by a given heating power, since a typical feature of type-I ELMy H-mode plasmas is that f_ELM increases with P_sep. During the transport simulation, we make the pressure decrease when an MHD mode is unstable to express an ELM. The diffusivity in the inter-ELM phase and the decrease in the pressure due to ELMs are to match given $f_\mathrm{ELM}\Delta W_\mathrm{ELM}/P_\mathrm{sep}$ and f_ELM.

For the sake of simplicity, we use a given density profile and a given pedestal width. If a pressure limit is determined by the MHD stability analysis, we need to evaluate the heat diffusivity in the inter-ELM phase and the amount of the temperature reduction due to ELMs to predict the time evolution of the temperature profile. To determine these unknown parameters to match the given $f_\mathrm{ELM}\Delta W_\mathrm{ELM}/P_\mathrm{sep}$ and f_ELM, we introduce adjustable profiles, fac_χ and fac_T, as shown in Figs. 2(a) and (b). For the heat diffusivity in the inter-ELM phase, the critical gradient model [3] is used in the core region, and the diffusivity in the pedestal region is evaluated by multiplying the diffusivity given by the critical gradient model and fac_χ. Here, fac_χ is defined as $\mathrm{fac}_\chi = f(\rho_\mathrm{ped})/f(\rho)$, where ρ_ped is value of the normalized minor radius at the pedestal shoulder, and $f(\rho)$ is given as a Gaussian distribution: $f(\rho) = (2\pi c_\chi^2)^{-0.5}\exp\left(-\frac{(\rho-(1+\rho_\mathrm{ped})/2)^2}{2c_\chi^2}\right)$. For the temperature reduction due to ELMs, the temperature is multiplied by fac_T, which is defined as $\mathrm{fac}_T = \left(0.5\cos\left(\frac{\pi}{1-\rho_\mathrm{ELM}}(\rho-\rho_\mathrm{ELM})\right)+0.5\right)c_T + (1-c_T)$. Here, the temperature is assumed to be reduced from $\rho = \rho_\mathrm{ELM}$ to $\rho = 1.0$. As the experimental observation indicates ρ_ELM is located farther inside than ρ_ped [4], we use $\rho_\mathrm{ped} = 0.96$ and $\rho_\mathrm{ELM} = 0.92$ in this paper. For a given combination of c_χ and c_T, $f_\mathrm{ELM}\Delta W_\mathrm{ELM}/P_\mathrm{sep}$ and f_ELM can be estimated using the time evolution of the temperature predicted by the transport simulations.

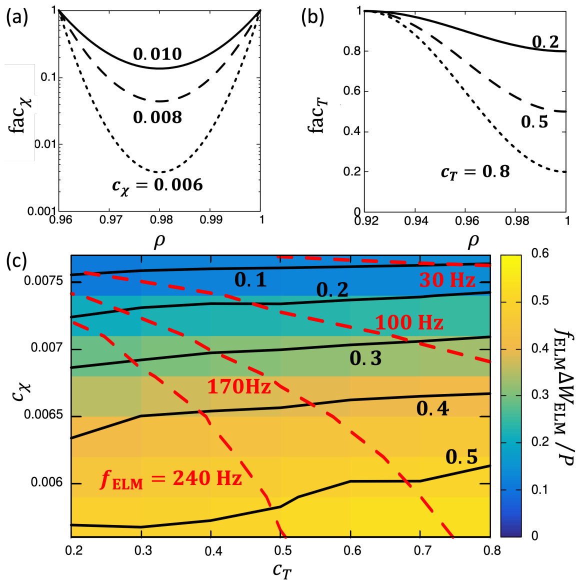

Figure 2. Radial profiles of (a) fac_χ and (b) fac_T. (c) Dependence of $f_\mathrm{ELM}\Delta W_\mathrm{ELM}/P_\mathrm{sep}$ (heat map and solid black lines) and f_ELM (broken red lines) on c_χ and c_T.

In this section, the transport simulations are presented assuming a JET plasma shown with a red circle in Fig. 1 and an ITER-like plasma. The calculation results for the JET plasma with different combinations of c_χ and c_T are shown in Fig. 2(c). Here, the plasma parameters are $I_\mathrm{p} = 2.0$ MA, $B_\mathrm{T} = 2.1$ T, the neutral beam heating power $P = 9.5$ MW, $f_\mathrm{ELM} \sim 30$Hz, and $f_\mathrm{ELM}\Delta W_\mathrm{ELM}/P_\mathrm{sep} \sim 0.3$. A pressure limit is given as the MHD stability constraint by using the

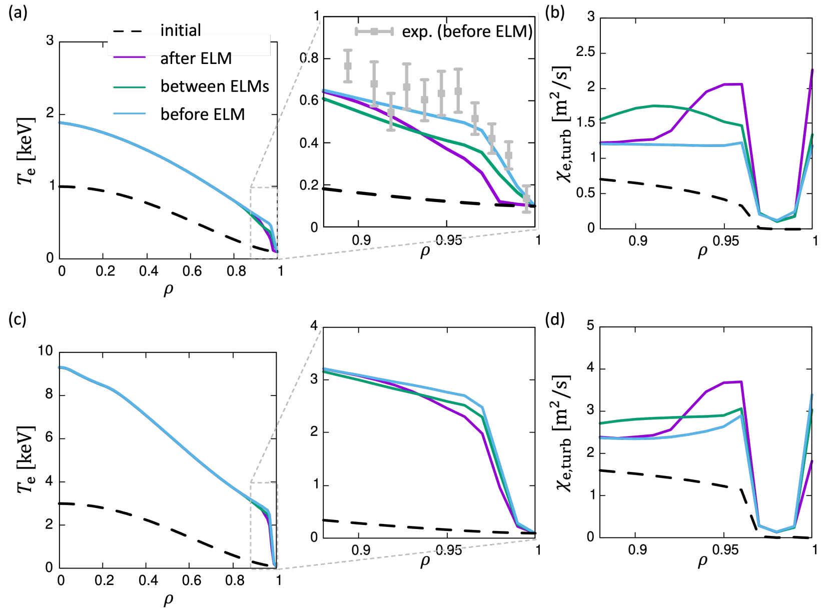

Figure 3. Radial profiles of (a), (c) the temperature and (b), (d) the heat diffusivity, assuming (a), (b) a JET-like plasma and (c), (d) a ITER-like plasma.

experimental value. As the simulations do not consider the particle loss with a fixed density profile, we have tried to find the combination of c_χ and c_T that satisfies $f_{\mathrm{ELM}} \sim 30$ Hz and $f_{\mathrm{ELM}}\Delta W_{\mathrm{ELM}}/P_{\mathrm{sep}} \sim 0.1$. In this case, $\Delta W_{\mathrm{ELM}} \sim 0.03$ MJ. Such a condition is obtained with $c_\chi = 0.0076$ and $c_T = 0.75$, and the temperature and heat diffusivity profiles are predicted (Figs. 3(a) and (b)). We have also searched for the condition that satisfies $f_{\mathrm{ELM}} \sim 30$ Hz and $f_{\mathrm{ELM}}\Delta W_{\mathrm{ELM}}/P_{\mathrm{sep}} \sim 0.1$ for the ITER-like plasma: the major radius $R = 6.4$ m, the minor radius $a = 2.0$ m, $I_{\mathrm{p}} = 4.7$ MA, $B_{\mathrm{T}} = 1.8$ T, and the electron cyclotron heating power $P = 30$ MW. In this case, $\Delta W_{\mathrm{ELM}} \sim 0.1$ MJ. The estimated coefficients are $c_\chi = 0.00675$ and $c_T = 0.30$, and the predicted temperature and heat diffusivity profiles are shown in Figs. 3(c) and (d). In these transport simulations, the pressure limit was a fixed input. To perform transport simulation and the MHD stability analysis simultaneously, we have developed a rapid MHD stability model using a NN model, as presented in the next section.

NN based ideal MHD stability model

If the condition of ELM occurrence is determined using the ideal MHD stability code MARG2D [5], it would take a prohibitively long time to perform a transport simulation, since each stability analysis requires about 60 seconds. We have constructed a NN based, MARG2D-NN, which predicts stabilities of toroidal modes of $n = 1, 2, 3, 4, 5, 6, 8, 10, 15, 20,$ and 30. The inputs of MARG2D-NN are the radial profiles of the electron density, the electron and ion temperatures, the safety factor, the current, the ellipticity, and the triangularity. MARG2D-NN has been constructed by supervised learning with a fully connected NN model. Training data were generated by MARG2D calculations with different profile combinations. In the training datasets, unstable and stable cases are labeled as unity and zero, respectively. An input case is classified as unstable when the sigmoid output exceeds 0.5. The MARG2D-NN predicts the stability in about 10^{-4} seconds, and the accuracy is higher than 95 %.

Transport simulations of H-mode plasmas with ELMs

The empirical transport model and MARG2D-NN have been introduced into the transport code TRESS. We have performed the integrated simulations assuming the ITER-like plasma. We fix the density profile, ρ_{ped} and ρ_{ELM}. We do not solve the magnetic equilibrium, but the change in the bootstrap current due to the change in the temperature profile is considered. The integrated simulation is executed with $c_\chi = 0.00675$ and $c_T = 0.30$, as shown in Fig. 4. In the simulation, the temperature increases from the initial profile, and goes into the ELM phase, where the temperature changes oscillatory (Fig. 4(a)). The MHD stability is analyzed by MARG2D-NN at all time steps, showing that the $n = 4$ is most unstable and determines the pedestal height (Fig. 4(b)). As the simulation takes only about 50 seconds, we can repeat it with different combinations of c_χ and c_T.

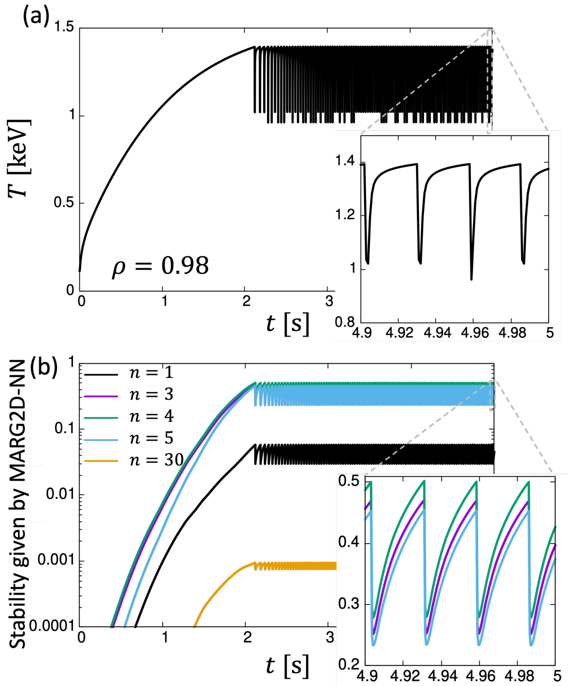

Figure 4. The time evolution of (a) the temperature at $\rho = 0.98$ and (b) the output of MARG2D-NN given as the MHD stability.

Summary

We have constructed the empirical transport model for the edge region and the NN based ideal MHD stability model. The time evolution of the temperature profile during ELM cycles can be predicted when the experimental conditions, f_{ELM} and $f_{\text{ELM}}\Delta W_{\text{ELM}}/P_{\text{sep}}$, are provided. We will develop a fast surrogate model for the magnetic equilibrium and perform transport, MHD stability, and magnetic equilibrium coupling simulations in the future.

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