FAST RESPONSES IN L/H TRANSITION

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Abstract

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An equation which includes the non-local effect in the heat flux is introduced to study the transient transport phenomena. A non-local heat flux, which is expressed in terms of the integral equation, is superimposed on the conventional form of the heat flux. This model is applied to describe the fast responses in the transition from Low confinement mode (L-mode) to High confinement mode (H-mode). A small fraction of non-local component in the heat flux is found to be very effective in modifying the response against L/H transition. The transient features of the transport property, which are observed in the response of heat pulse propagation, are qualitatively reproduced by the transport simulations based on this model.

1. INTRODUCTION

H-mode [1] has been subject to intensive studies in plasma confinement. The role of radial electric field on H-mode was theoretically predicted [2] and is widely recognized in experiments. ITER design is made relying on H-mode operation. However, there still exists a mystery. The plasma profile in core region was found to change in a much faster time scale than the diffusion time scale after the L/H transition [3]. Such fast responses are seen in the heat pulse propagations of the sawteeth, heating power modulation, injection of the impurity, etc. Understanding of the mechanism of the fast response not only reveals the physics of H-mode but also provides a dependable prediction for the burning dynamics in the core plasma of a fusion reactor, in which L/H (or H/L) transitions and ELMs could occur.

In this paper, we investigate a role of non-locality of plasma transport in the study of heat pulse propagation. For this purpose, a model equation is chosen, in which the non-local effect is taken into account in the heat flux. A non-local heat flux, which is expressed in terms of an integral equation, is superimposed on the conventional form of the heat flux. This enables us to make an inductive extension of the local diffusive model to one with the non-local effect. The properties of this model are investigated by a transport simulation under L/H transition. The non-local model analysis will give us a new understanding for the transient transport in high temperature plasmas.

2. NON-LOCAL TRANSPORT MODEL

In this section, we present our model and explain its properties. To investigate the transient response of the electron temperature, let us start with the transport equation for the electron temperature,

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e(r,t)T_e(r,t)\right) = -\nabla\cdot q_e(r,t) + \Sigma Q(r) \tag{1}$$

where n_e, T_e, q_e and ΣQ represent the electron density, temperature, heat flux and sources/sinks, respectively. The boundary conditions are set to be $q_e(0,t) = 0$ and $T_e(a,t) = 0$, where a is the plasma minor radius. For simplicity, we assume that the density is constant in this model.

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The non-local transport model has been formulated and successfully applied to the problems of transient responses, i.e., power switching [4] and power modulation experiments in W7-AS [5]. Extending the analysis of the heat pulse propagation, we here study the fast responses in plasma profile after the L/H transition. A generalized formula of the heat flux is employed as,

$$q_e(r,t) = -\int_0^a n_e(r',t)\chi_e(r',t)K_l(r,r')\left[\lambda\nabla T_e(r,t) + \left(1-\lambda\right)\nabla' T_e(r',t)\right]dr' \qquad (2)$$

where χ_e is the heat diffusivity. The kernel is chosen as

$$K_l(r,r') \equiv \frac{r}{r'}\left[C_{local}\delta(r-r') + C_{global}\frac{1}{\sqrt{\pi}l}exp\left\{-\left(\frac{r-r'}{l}\right)^2\right\}\right] \qquad (3)$$

where l is the half width of non-local interactions, $\delta(r-r')$ is a delta function, and $\lambda(0 \le \lambda \le 1)$, C_{local} and C_{global} ($C_{local} + C_{global} = 1$) are numerical constants. The parameter λ represents the ratio of the role of the local temperature gradient in the non-local transport process. In the limit of $\lambda = 0$, the heat flux is reduced to that used in Ref [4, 5] and the non-locality is included in the heat flux through the $n_e(r',t)$, $\chi_e(r',t)$ and $\nabla' T_e(r',t)$. In the limit of $\lambda = 1$, the non-locality is included in the heat flux through the $n_e(r',t)$ and $\chi_e(r',t)$ only; The heat flux is proportional to the local temperature gradient and is independent of the temperature gradient away from the position r. The parameters C_{local} and C_{global} represent the ratio of the locality and the non-locality included in the transport process. In the limit of $C_{global} = 0$, the heat flux is reduced to the one of the local transport model, $q_e(r,t) = -n_e(r,t)\chi_e(r,t)\nabla T_e(r,t)$. The interaction of fluctuations with a short radial correlation length and those with a long correlation length $(\sim l)$ is modeled into the kernel of integral. The plasma turbulence due to the nonlinear excitation [6] could be a candidate to generate very long correlated structures across the magnetic field. In the limit $l \to 0$, the heat flux is reduced to the one of the local transport model. The weighting function r / r' is introduced to assure the condition, $q_e(0,t) = 0$. The source term, i.e., the power deposition profile, is modeled as $\Sigma Q(r) \propto exp\left[-(r/0.3a)^2\right]$. In the following calculations, the parameters are chosen as $\lambda = 0.5$, $C_{global} = 0.1$ and $l/a = 0.5$, and the electron density is fixed as $n_e = 5 \times 10^{19}\mathrm{m}^{-3}$.

3. SIMULATION RESULTS

The energy transport equation Eq. (1) is solved under the condition given in the previous section, and the temporal evolution of the temperature profile after the L/H transition is analyzed. In this calculation, JET-like parameters, i.e., major radius $R = 2.85$m, minor radius $a = 0.95$m and heating power $P = 10$MW, are used. Figure 1(a) shows the profiles of model thermal diffusivity. In L-mode regime, the heat diffusivity increases monotonically with r. In H-mode regime, the diffusivity is reduced in the edge region of the plasma ($r/a \ge 0.8$). In each case, the diffusivity is assumed to be constant in time. Using these diffusivity profiles for L- and H-mode, the temperature profiles in the L- and H-mode steady state T^L, T^H are obtained, which are shown in Fig. 1(b).

We investigate the transient response after L/H transition. Fig. 2 shows the temporal evolution of the electron temperature ΔT in the core region (at $r/a = 0.1$), where ΔT is defined as $\Delta T \equiv (T - T^L) / (T^H - T^L) \times 100$, which represents the deviation from L-mode temperature profile. The solid line and dashed line correspond to the non-local model ($C_{global} = 0.1$) and local model ($C_{global} = 0$), respectively. The horizontal axis is normalized to the typical time, τ. Now we set to be $\tau = 40$ msec. L/H transition occurs at $t/\tau = 0$. Right after the transition in χ_e occurs in the edge region, the temperature of the core plasma responds. It's time scale is much faster than that in diffusion process. The non-local transport model reproduces the fast response in the core plasma after L/H (or H/L) transition. Furthermore, this model also reproduces the fast response from the plasma

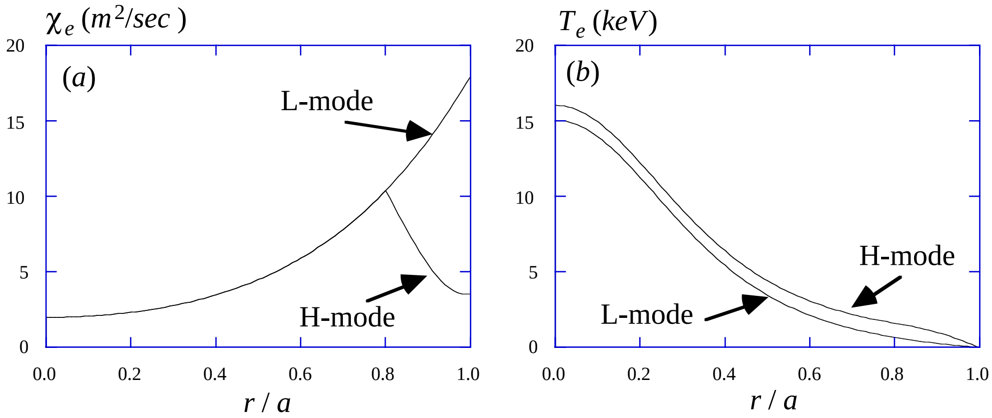
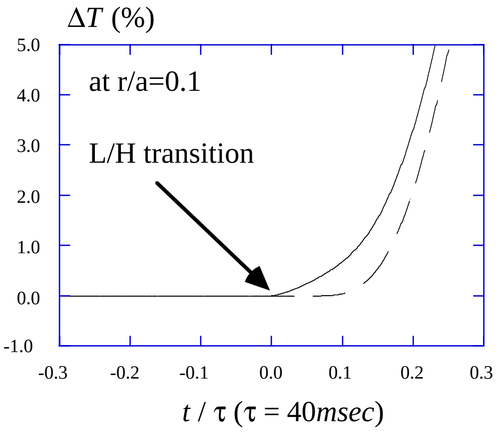


Fig. 1. *The profiles in L and H mode of* (*a*) *modeled diffusivity and* (*b*) *temperature. The temperature profiles are obtained by use of the diffusivity in* (*a*). *In this case, it is assumed to be major radius* $R = 2.85m$, *minor radius* $a = 0.95m$ *and heating power* $P = 10MW$.



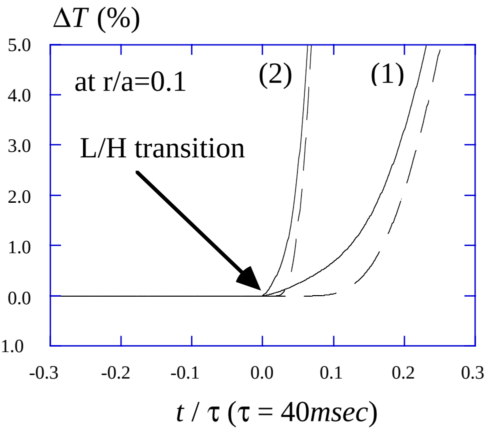


Fig. 2. *The temporal evolution of the temperatue observed at* $r/a = 0.1$. *The solid and dashed lines are obtained using non–local and local model, respectively. Parameters are chosen as the same in Fig.* 1.

Fig. 3. *The dependence of transient response on machine size. Parameters are chosen as in* (1) $R = 2.85m$, $a = 0.95m$ *and* $P = 10MW$ *and in* (2) $R = 1.65m$, $a = 0.5m$ *and* $P = 2MW$.

core to the edge observed in the heat pulse propagation experiments [4, 5]. From our simulation, it is found that $C_{global} = 0.1$ is enough to reproduce the fast responses observed in experiment [3].

The fast responses reproduced by the non-local model is almost independent of the functional form of χ_e. We also investigated the transient response using the diffusivity models of $\chi_e \propto T_e$, ∇T_e. Similar fast responses were obtained. Thus we can conclude that the fast response is reproduced using the non-local model independent of the diffusivity models. The quantitative difference of the transient response with the different χ_e models can be seen by the hysteresis curve in the flux-gradient phase space same as the previous study for heat pulse propagation or power modulation experiments [4, 5], where the heat flux follows one characteristic line in the local transport model, on the other hand, heat flux in the core is affected by the change in the edge region at the transition, being faster than the change of temperature gradient in the non-local model.

Next we investigate the dependence of the transient response on machine size, which is shown in Fig. 3. The curves (1) are calculated with the JET-like parameters and the curves (2) are calculated with the ASDEX-Upgrade-like parameters ($R = 1.65$m, $a = 0.5$m and $P = 2$MW), using the diffusivity profile given in Fig. 1(a) in each case. The transient responses are observed at $r / a = 0.1$. The solid lines and dashed lines correspond to the non-local model and local model, respectively.

Since ΔT is independent of the heating power when the diffusivity does not depend on the temperature or temperature gradient, the dependence of transient response on machine size is extracted from Fig. 3. In both cases with JET-like and ASDEX-Upgrade-like parameters, the temperature calculated by the non-local model suddenly starts to increase when L/H transition occurs. On the other hand, the temperature calculated by the local model tends to increase after the time delay of about 4 msec in the case of JET-like parameters and about 1 msec in the case of ASDEX-Upgrade-like parameters. Therefore, the difference in the responses after L/H transition, whether the local model or the non-local model are adopted, appears clearly in the large machine than in the small machine.

4. SUMMARY AND DISCUSSION

In this paper, a transport model, in which the non-local effect is taken into account, was used to analyze the fast response after L/H transition. The interaction of fluctuations with a short radial correlation length and those with a long correlation length $\left(\sim l\right)$ is modeled into the kernel of integral. The fast response in the core plasma after L/H (or H/L) transition was reproduced based on this model. It was found that $C_{global} = 0.1$ is enough to reproduce the fast responses observed in experiment [3]. If there is a long wavelength fluctuation which induces the non-local effect, the pulse after L/H or H/L transition could propagate faster than the pulse expected in the diffusive, local (microscopic) model. (However, in the case of H/L transition, the effect of $\boldsymbol{E} \times \boldsymbol{B}$ shearing might change the mode structure, therefore, a shorter wave length mode becomes important in the edge region. Thus we expect that the pulse will propagate more slowly in the case of H/L transition than in the case of L/H transition.) The dependence of the transient response after L/H transition on the machine size was also investigated. It was shown that the fast response after L/H transition appears clearly in the large machine than in the small machine. A model of global change of χ_e was proposed to analyze the L/H transition in JET [7]. Our method provides a more general model, by which other types of transient phenomena could be explained in a unified way.

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