§4. Test of a Non-Diffusive Transport Model for Dynamics in LHD Plasma

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In a local diffusive picture of transport, the transport flux is expressed in terms of mean parameters and their spatial derivatives at the same location. However limitations of a local diffusive picture of transport is widely recognized during recent years; A new global hysteresis in the gradient-flux relation was discovered [1]. The heat flux is a multiple-valued function of gradient, so that the dynamics in the temperature perturbation is far from a simple diffusive response. The non-diffusive transport has a critical impact on the predictive capability of future burning plasmas and thus should be clarified. We applied the telegraph equation model to the heat pulse propagation experiment in LHD [2].

Here we focus on the dynamic response. For perturbations, the energy balance in the no heat source region can be written as follows:

$$\frac{3}{2}n\frac{\partial \delta T}{\partial t}+\nabla\delta q=0\,, \qquad (1)$$

where n is the electron density and δT, δq are perturbations in the temperature and heat flux respectively. The turbulence has its own relaxation time, thus the heat flux is assumed to converge to the stationary state with a finite relaxation time τ as follows:

$$\frac{\partial \delta q}{\partial t}=-\frac{\delta q-\delta q_0}{\tau}\,, \qquad (2)$$

where q_0 is steady state flux and related to the temperature gradient by $\delta q_0 = -n\chi\nabla\delta T$. Combining (1) and (2) gives the telegraph equation:

$$\frac{\partial^2 \delta T}{\partial t^2}+\frac{1}{\tau}\frac{\partial \delta T}{\partial t}-\frac{2\chi}{3\tau}\nabla^2\delta T=0\,. \qquad (3)$$

We assumed $\nabla\delta T$, which is quite similar to the experimental observation, and calculated δq at three different values of $\omega\tau$, where ω is heat modulation frequency. The delay between the time-to-peak of δq increases with increase in τ as shown in Fig. 1. In the limit of short relaxation times, $\tau \sim 0$ (i.e. diffusive transport), the delay time converges to 0. Figure 2 indicates that telegraph equation model can reproduce a hysteresis in the flux-gradient diagram. In the limit of $\tau = 0$, the heat flux becomes single valued function of the gradient. In the case of finite τ, however, the heat flux changes following the change in the gradient, i. e. the model gives a counterclockwise rotation. While the experimental results show clockwise rotation (Fig. 5 in [1]).

The present model is not enough to understand the observations on LHD. The present model gives the relation

$$\delta q=-n\chi\int_0^t dt'\exp\left(\frac{t'-t}{\tau}\right)\nabla\delta T \qquad (4)$$

i.e., the heat flux changes following the change of the gradient. The hysteresis between the temperature gradient and heat flux thus cannot be explained by the present model. Further extensions of the model are needed to fully understand observations on the LHD.

[1] S. Inagaki, et. al., Nucl. Fusion **53**, 113006 (2013).
[2] S. Inagaki et. al., Plasma Fusion Res. **10** 1203002 (2015).

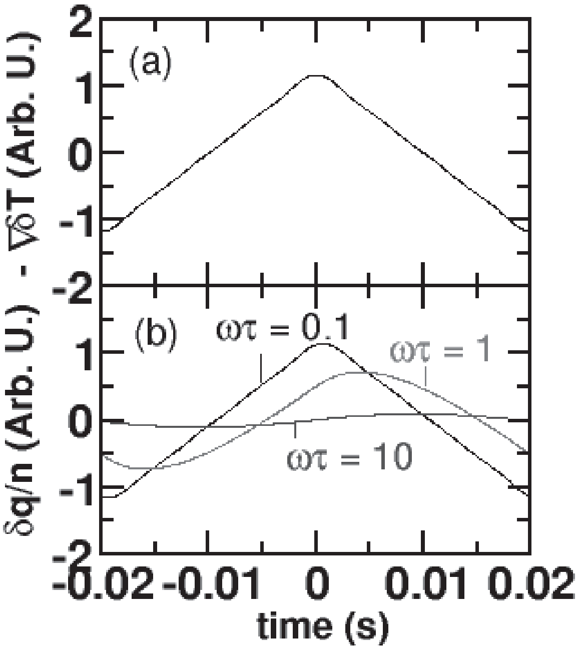

Fig. 1 Temporal evolution of (a) experimentally observed temperature gradient and (b) computed heat flux from the telegraph equation at three different $\omega\tau$.

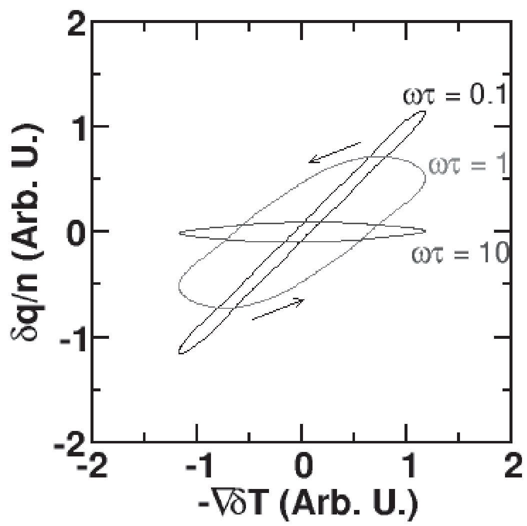

Fig. 2 Flux-gradient relation computed from the telegraph equation. Arrows denote direction of variation.