§6. Reduced Model for Ion Temperature Gradient Turbulent Transport Based on Gyrokinetic Simulations

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A reduced model for ion temperature gradient (ITG) turbulent transport in helical plasmas is developed based on nonlinear gyrokinetic simulations. In many gyrokinetic simulations of ITG turbulent transport in helical plasmas by using the GKV-X code[1)] with various input parameters such as the density and temperature gradients and local shears, it was found that the ion heat transport coefficient in the gyro-Bohm unit $\chi_\mathrm{i}/\chi_\mathrm{i}^\mathrm{GB}$ depends on the squared turbulent potential fluctuation $\mathcal{T} = (1/2)\sum_{k_x,k_y\neq 0}\langle|e\phi_{k_x,k_y}R_0/T_\mathrm{i}\rho_\mathrm{ti}|^2\rangle$, and the squared amplitude of zonal flow potential $\mathcal{Z} = (1/2)\sum_{k_x}\langle|e\phi_{k_x,0}R_0/T_\mathrm{i}\rho_\mathrm{ti}|^2\rangle$ through the following function [2)]

$$\frac{\chi_\mathrm{i}}{\chi_\mathrm{i}^\mathrm{GB}} = \frac{C_1\,\mathcal{T}^\alpha}{C_2 + \mathcal{Z}^{1/2}/\mathcal{T}} \equiv \mathcal{F}(\mathcal{T},\mathcal{Z}). \qquad (1)$$

Here, $\alpha = 0.36$, $C_1 = 0.067$ and $C_2 = 0.0082$. And ρ_ti is the ion thermal gyro radius, R_0 is the major radius of the field, the flux-surface average is denoted by $\langle\cdots\rangle$, and (k_x, k_y) represent wavenumbers in radial and poloidal directions, respectively. In order to construct a reduced model for the turbulent transport, the relations between the nonlinear simulations and linear analyses are considered. From the linear analyses, the squared turbulent potential fluctuation can be represented by the linear instability growth rates γ_k as $\mathcal{T} = C_\mathcal{T}\sum_{k_y}\tilde{\gamma}_k/\tilde{k}_y^2$ with $C_\mathcal{T} = 9.8\times 10^1$, where the growth rate and the wavenumber are normalized as $\tilde{\gamma} \equiv \gamma/(v_\mathrm{ti}/R_0)$ and $\tilde{k} \equiv k\rho_\mathrm{ti}$, respectively. The interaction between zonal flows and turbulence should also be incorporated into the reduced model. It is found that the linear response functions of the zonal flow potential $\phi_{k_x}(t)/\phi_{k_x}(0)$ is correlated with the zonal flow amplitude, $\sqrt{\mathcal{Z}/\mathcal{T}} = C_\mathcal{Z}\tilde{\tau}_\mathrm{ZF}$, with $C_\mathcal{Z} = 0.202$, where $\tilde{\tau}_\mathrm{ZF} \equiv \tau_\mathrm{ZF}/(R_0/v_\mathrm{ti})$ with the zonal flow *decay time*, $\tau_\mathrm{ZF} \equiv \int_0^{\tau_\mathrm{f}} dt\ \phi_{k_x}(t)/\phi_{k_x}(0)$. Here, we used $\tilde{k}_x = 0.25$ and $\tau_\mathrm{f} = 25\ R_0/v_\mathrm{ti}$. If we substitute the expressions for $\mathcal{T}$ and $\mathcal{Z}$ into the function $\mathcal{F}$ of Eq.(1) using the linear results γ_k and τ_ZF , we can obtain a reduced model which represents the turbulent ion heat diffusivity in terms of the linear simulation results[3)],

$$\frac{\chi_\mathrm{i}^\mathrm{model}}{\chi_\mathrm{i}^\mathrm{GB}} = \frac{A_1\left(\sum_k \tilde{\gamma}_k/\tilde{k}_y^2\right)^\alpha}{A_2 + \tilde{\tau}_\mathrm{ZF}/\left(\sum_k \tilde{\gamma}_k/\tilde{k}_y^2\right)^{1/2}}\ , \qquad (2)$$

where $A_1 = C_1 C_\mathcal{T}^{\alpha+1/2} C_\mathcal{Z}^{-1}$ and $A_2 = C_2 C_\mathcal{T}^{1/2} C_\mathcal{Z}^{-1}$. As shown in Fig. 1, the model calculations in the LHD high ion temperature plasma can reproduce the nonlinear results. Figure 2 shows the results of comparison for the ion heat transport coefficient between nonlinear gyrokinetic simulation results $\chi_\mathrm{i}^\mathrm{NL}$ and the model predictions $\chi_\mathrm{i}^\mathrm{model}$ for a wide parameter range with the root mean square of the relative errors, $[\chi_\mathrm{i}^\mathrm{NL}/\chi_\mathrm{i}^\mathrm{Model} - 1]$, given by $\sigma = 0.168$. The present transport model is constructed by combination of the linear instability and zonal flow response analyses and elaborate nonlinear gyrokinetic simulations, and involves a similarity with the conventional mixing length ansatz but with explicit introduction of the zonal flow contribution. The basic idea of the model is also applied to tokamak configurations. The present model, which requires extremely smaller computational cost than that of the nonlinear simulation, can be applied to an integrated transport code, and to a survey of the transport levels in a wide space of multiple parameters.

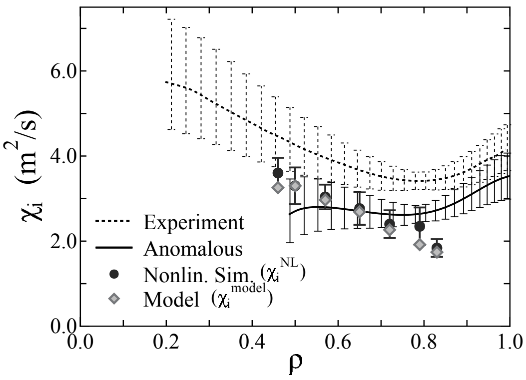

Fig. 1: Radial profiles of ion heat diffusivity in the high-T_i LHD plasma obtained from the experiment (dotted curve), the nonlinear simulations (blue symbols), and the model predictions (red diamonds). The solid curve shows the anomalous contribution of the experimental results.

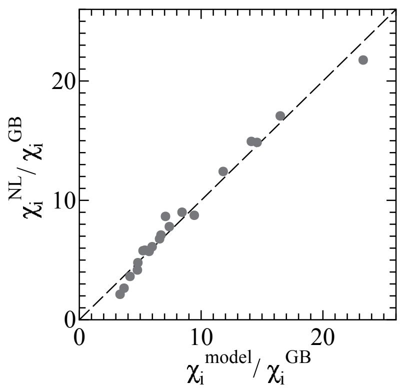

Fig. 2: Comparison of the ion heat diffusivities between the nonlinear simulation results $\chi_\mathrm{i}^\mathrm{NL}$ and the model predictions $\chi_\mathrm{i}^\mathrm{model}$.

1) M. Nunami *et al.*, Plasma Fusion Res. **5** (2010) 016.

2) M. Nunami *et al.*, Plasma Fusion Res. **8** (2013) 1203019.

3) M. Nunami *et al.*, Phys. Plasmas **20** (2013) 092307.