ENERGY EXCHANGE BETWEEN ELECTRONS AND IONS INDUCED BY ITG-TEM TURBULENCE

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Microturbulence in magnetically confined plasmas contributes to energy exchange between particles of different species as well as the particle and heat fluxes[1-5]. In this study, gyrokinetic simulations are performed with the GKV code[6] to evaluate the effect of microturbulence on the energy exchange between electrons and ions in tokamak configuration. In particular, energy exchanges due to ion temperature gradient (ITG) and trapped electron mode (TEM) turbulence are investigated here.

It is found that the ITG turbulence transfers energy from ions to electrons regardless of whether ions or electrons are hotter, which is in marked contrast to the energy transfer by Coulomb collisions[7]. This implies that the ITG turbulence should be suppressed from the viewpoint of sustaining the high ion temperature required for fusion reactions since it prevents energy transfer from alpha-heated electrons to ions. Furthermore, linear and nonlinear simulation analyses confirm the feasibility of quasilinear modeling for predicting the turbulent energy exchange[7]. It is also clarified that TEM turbulence transfers energy from electrons to ions, and the direction of energy exchange in mixed ITG-TEM turbulence depends on the dominant instability. In other words, the direction is basically from particle species with larger entropy produced by energy transport to other particle species.

The GKV code solves the gyrokinetic equations for the perturbed distribution functions based on the Eulerian scheme. Most of plasma and geometric parameters used in the simulations are the same values as in the Cyclone DIII-D base case (CBC)[8]. In order to compare energy exchange by Coulomb collision and microturbulence and to simulate turbulence with several instability modes, electron and ion temperature gradient lengths $R_0/L_{Ts}(s=e,i)$, temperature ratio T_e/T_i are varied.

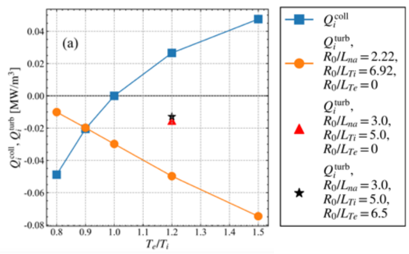

Fig. 1 Comparison of energy exchanges due to Coulomb collisions (blue) and turbulence(orange)[7]. This is the case of $\delta \equiv \rho_{ti}/R_0 = 9.6\times10^{-4}$, $n_e = 2\times10^{19}\ \mathrm{m}^{-3}$, $T_i = 0.9\ \mathrm{keV}$. Red triangles and black stars indicate turbulent energy exchanges obtained from simulations with plasma parameters in the case of DIII-D128913[9].

The comparison between collisional and turbulent energy transfers from electrons to ions, $Q_i^{\rm coll}\left(=-Q_e^{\rm coll}\right)$ and $Q_i^{\rm turb}\left(=-Q_e^{\rm turb}\right)$ are shown in Fig. 1. We can identify a difference between the directions of the two energy transfers. Coulomb collisions always transfer energy from higher-temperature particles to lower-temperature ones. Thus, when T_e/T_i is less (more) than unity, $Q_i^{\rm coll}$ is negative (positive). On the other hand, the ITG turbulence always transfers energy from ions to electrons regardless of T_e/T_i. We see that $Q_i^{\rm coll}$ and $Q_i^{\rm turb}$ take opposite signs to each other when $T_e/T_i > 1$. It is reported in Ref. [5] that the turbulent energy exchange has a negligible effect on the simulation for predicting the temperature profile

Tab. 1 Estimated effects of turbulent energy fluxes $\mathcal{E}_s^{\rm turb}$ and energy exchanges in the local energy balance at $r(=0.5\,a)$ using the result of the black star in Fig. 1. The estimation assumes the case of $n_e = 2\times10^{19}\ \mathrm{m}^{-3}$ and $T_i = 0.9, 2.0, 10\ \mathrm{keV}$. The effects of the divergence of the energy fluxes are roughly estimated by $\mathcal{E}_s^{\rm turb}/r$ for comparison with the effect of the energy exchanges on temperature profiles. $Q_i^{\rm turb}, Q_i^{\rm coll}, \mathcal{E}_s^{\rm turb}/r$ are expressed in [MW/m^3], and $4\pi^2 r R_0 \mathcal{E}_s^{\rm turb}$ are in [MW]. The ITER-like conditions[10] of heating power for a core plasma $P_{\rm h} = P_{\rm in} + P_\alpha = 150\ \mathrm{MW} \simeq 4\pi^2 r R_0\left(\mathcal{E}_e^{\rm turb} + \mathcal{E}_i^{\rm turb}\right)$ and the major(minor) radius $R_0 = 6.2\ \mathrm{m}\,(r = 0.5\,a = 1.0\ \mathrm{m})$ are used with $T_e/T_i = 1.1$ to estimate permissible energy fluxes divided by r as $\mathcal{E}_i^{\rm turb}/r = 0.40\mathrm{MW/m^3}$ and $\mathcal{E}_e^{\rm turb}/r = 0.20\ \mathrm{MW/m^3}$, from which $Q_i^{\rm turb} \sim 0.5(r/R_0)\mathcal{E}_i^{\rm turb}/r = 0.020\ \mathrm{MW}$ is derived, respectively. Additionally, $Q_i^{\rm coll}$ is evaluated $0.10\ \mathrm{MW/m^3}$ under Case A ($n_e = 1\times10^{20}\ \mathrm{m}^{-3}$, $T_i = 10\ \mathrm{keV}$) and $0.017\ \mathrm{MW/m^3}$ under Case B ($n_e = 0.5\times10^{20}\ \mathrm{m}^{-3}$, $T_i = 20\ \mathrm{keV}$).

T_i (keV)	$Q_i^{\rm turb}$	$Q_i^{\rm coll}$	$\mathcal{E}_i^{\rm turb}/r$	$\mathcal{E}_e^{\rm turb}/r$	$4\pi^2 r R_0\left(\mathcal{E}_i^{\rm turb}+\mathcal{E}_e^{\rm turb}\right) \sim P_{\rm h}$
0.9	-0.013	0.027	0.27	0.15	2.7
2.0	-0.096	0.017	2.0	1.1	20
10	-5.4	0.008	111	62	1110
10 (under the ITER-like conditions, Case A)	-0.020	0.10	0.40	0.20	150
20 (under the ITER-like conditions, Case B)	-0.020	0.017	0.40	0.20	150

in the case of DIII-D128913[9]. Here, we also compare that case with CBC in Fig. 1. These plots indicate that the magnitude of turbulent energy exchange becomes smaller than that of the collisional one at a low ion temperature gradient, which is consistent with the result of Ref. [5]. However, even when the temperature gradient is fixed to the same value, turbulence can dominate in the energy exchange when the plasma temperature increases.

Table 1 shows estimated effects of energy exchange with different plasma temperatures and fixed temperature ratio $(T_e/T_i = 1.2)$. At $T_i = 0.9\,\mathrm{keV}$, the magnitude of collisional energy exchange is greater than that of turbulent one, but at $T_i = 2.0\,\mathrm{keV}$ the turbulent energy exchange is predominant. The case of $T_i = 10\,\mathrm{keV}$ calculated by the same way is unrealistic since the estimated heating power for a core plasma $P_\mathrm{h} \simeq 4\pi^2 r R_0 \left(\mathcal{E}_e^\mathrm{turb} + \mathcal{E}_i^\mathrm{turb}\right) = 1110\ \mathrm{MW}$ is too large, so we use the ITER-like conditions[10] to estimate permissible energy fluxes divided by r as $\mathcal{E}_i^\mathrm{turb}/r = 0.40\ \mathrm{MW/m^3}$ and $\mathcal{E}_e^\mathrm{turb}/r = 0.20\ \mathrm{MW/m^3}$. The energy transfer from electrons to ions in the ITG turbulence can be estimated using Eq. (50) of Ref. [7] as $Q_i^\mathrm{turb} \sim C\mathcal{E}_i^\mathrm{turb}/R_0$ where $C = 0.5$ is chosen to fit the simulation results. This formula to estimate Q_i^turb is found to well explain the simulation results in our work and others in Refs. [7, 11, 12]. We see that, in the ITG turbulence under the ITER-like conditions(Case B: $R = 6.2\ \mathrm{m}$, $T_i = 20\ \mathrm{keV}$, $n_e = 0.5 \times 10^{20}\mathrm{m^{-3}}$, $T_e/T_i = 1.1$ at $r = 1\ \mathrm{m}$), the turbulent ion cooling can be significant compared with collisional ion heating so that the turbulent energy exchange should be taken into account for predicting energy distribution for electrons and ions in future reactors.

From the investigation of energy exchange in pure ITG turbulence, we conjecture that energy is generally transferred by turbulence from a particle species with larger entropy production due to particle and heat transport. To verify this conjecture, the energy exchange and entropy balance of each particle species due to ITG-TEM turbulence are investigated. It is found that pure TEM turbulence transfers energy from electrons to ions, which is the opposite direction to that of ITG turbulence. The energy exchange mainly consists of the cooling of ions (electrons) in the ∇B-curvature drift motion and the heating of electrons (ions) streaming along a field line in ITG (TEM) turbulence, respectively. Figure 2 shows the results of nonlinear calculations for mixed ITG-TEM turbulence as a function of the difference between entropy productions. It indicates that the sign of energy exchange (direction of energy exchange) basically agrees with the sign of the difference between the entropy productions for electrons and ions.

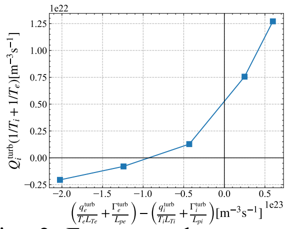

Fig. 2 Energy exchange as a function of the difference in entropy production for electrons and ions.

The feasibility of a quasilinear model for turbulent energy exchange is investigated to incorporate the effect into global transport simulation. In Fig. 3, the ratio of the turbulent energy exchange Q_i^turb to the squared electrostatic potential amplitude in the nonlinear ITG simulation is compared with that predicted from the linear simulation. We can find that the ratio calculated by linear simulation agrees with that by nonlinear calculation within an error margin of 30% or less in the colored wavenumber regions, where more than 80% of the total value of the energy exchange can be accounted for. Therefore, the quasilinear model can effectively predict nonlinear results of the energy exchange in the ITG turbulence.

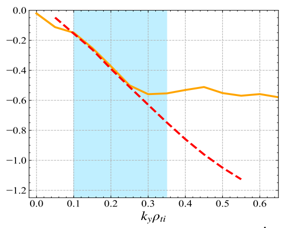

Fig. 3 The ratio of the turbulent energy transfer Q_i^turb to the squared electrostatic potential amplitude in the nonlinear ITG simulation (solid line) and that predicted from the linear simulation (dashed line)[7].

In this study, the effect of ITG turbulence on the energy exchange between electrons and ions in tokamak plasmas is investigated. The ITG turbulence is found to be significant in the energy exchange in equithermal or high-temperature plasmas. It is also shown that the direction of net energy transfer can be opposite to that of the collisional one. It is shown in Ref. [12] that, when the transition from the ITG turbulence to the electromagnetic turbulence driven by the kinetic ballooning mode (KBM) occurs with increasing beta, the turbulent energy transfer from ions to electrons becomes more significant. Therefore, the ITG turbulence is anticipated to prevent energy transfer from alpha-heated electrons to ions. To incorporate the effect of turbulent energy exchange with the quasilinear model, the predictability is confirmed in the case of ITG turbulence. In addition, it is found that turbulence tends to cause energy exchange from particle species with large entropy production to other species.

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