§18. Fluid Simulation of Tokamak Turbulence with Zonal Flow Closure Model

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Energy spectrum of ITG turbulence is studied by using the nonlinear fluid simulation. Barnes et al.[1] studied scaling of turbulent energy spectrum based on the gyrokinetic simulation. They use an energy-like quantity $W \sim \delta f^2$, which is originally a kinetic entropy[2]. In our fluid case, we consider an energy as $W \sim u_{Ex}^2 + u_{Ey}^2$, which is perpendicular ExB flow energy. By using this, a result of Perseval's identity is $\int dk_y \rho_i \, E(k_y) \sim \Sigma_{kx,ky}(k_x^2+k_y^2)|\Phi_{kx,ky}| \, (R/\rho_i)$, and eq.(11) of Barnes et al is,

$$E(k_\perp) \sim (\rho_i/R)^2 q^{-2/3} (R/L_T)^{4/3} (k_\perp \rho_i)^{-5/3}. \qquad \text{(a)}$$

This is a case of no zonal flow (ZF). Next we consider a case with ZF. As a result of elongation of eddy in the poloidal direction, it is assumed that $l_y^o \sim L_y \sim r_0 2\pi/(qn_0) \sim R(r_0/qR)(2\pi/n_0) \sim R$, i.e, taking typical scale of outer region to be fixed to l_x^o, we assume that l_y^o is a device size; $l_y^o \gg l_x^o$. Then eqs. (3) and (4) of Barnes are changed as follows,

$$v_{th}/l_{/\!/} \sim \tau_{nl}^{-1} \sim (v_{th}/R)(\rho_i/l_x)(\rho_i/R)\,\Phi_l$$

and

$$\tau_{nl}^{-1} \sim \omega_*^o \sim (\rho_i v_{th})/(l_x^o L_T)$$

From these, eqs. (6) and (7) of Barnes are changed to

$$\rho_i / l_x^o \sim L_T/qR$$

and

$$\Phi_l^o \sim (R/L_T)\,(R/\rho_i)$$

In considering characteristic perpendicular scale length to be l_x, energy transfer rate is

$$W/\tau_{nl} \sim (\rho_i/l_x)^3 \Phi_l^3 \,(\rho_i/R)\,(v_{th}/R) \sim \text{const.}$$

so that

$$\Phi_l \sim \Phi_l^o \sim (\rho_i/l_x^o)\,(l_x/\rho_i) \sim (1/q)(R/\rho_i)(l_x/\rho_i)$$

As a result, we have

$$E(k_\perp) \sim (k_x \rho_i)\,\Phi_{kx}^2 \sim (R/\rho_i)^2 (1/q^2)(k_x\rho_i)^{-1} \qquad \text{(b)}$$

Energy spectrum without ZF and with ZF are shown in Fig.1. In the inertial range ($k_\perp\rho_i \sim 0.5\text{-}1.0$), the scaling of top and bottom figures seem to follow eq.(a) and eq.(b) respectively.

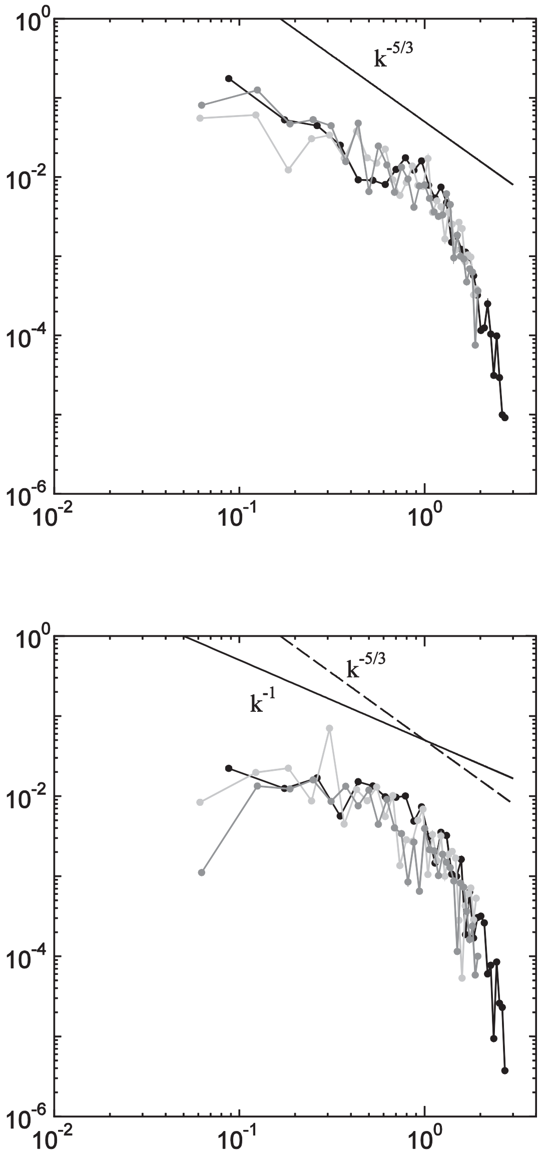

Fig. 1. Energy spectrum of result without ZF (top) and with ZF (bottom) as a function of $k_\perp\rho_i$.

1) M. Barnes, F. I. Parra, and A. A. Schekochihin, Phys. Rev. Lett **107**, 115003 (2011).
2) H. Sugama and W. Horton, Phys. Plsamas **4**, 405 (1997).