Theory of the Anomalous Transport Reduction

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There has been mounting evidence from laboratory and computer experiments that the reduction in turbulent transport by shearing by mean $\vec{E}\times\vec{B}$ flows and zonal flows is critical to the formation of transport barrier (e.g. the L-H transition and the formation of internal transport barrier). In particular, the recent theoretical study [1] has indicated that zonal flows play an important role in regulating turbulence before the L-H transition until the shearing by mean flows becomes dominant due to the steepening of the mean pressure gradient near the transition, keeping the plasmas in the H-mode after the transition. Therefore, the medelling of the formation of transport barrier requires a quantitative prediction as to how much flux is reduced by both mean and zonal flows. Here, we consider a few simple turbulence models to study the scaling of the transport with (mean or RMS) shearing rate and then to examine the model dependence of such scalings.

First, we examine how the mean shearing (with shearing rate Ω) affects the turbulent transport. In the passive scalar field model where random turbulence is arbitrarily specified, the transport is weakly reduced as Ω^{-1} while cross-phase is very weakly suppressed as $\Omega^{-1/6}$ [2]. In simple interchange and ion-temperature gradient turbulence models where turbulent flow is allowed to evolve dynamically, the transport of particle and heat is more strongly reduced with shearing rate Ω as $\Omega^{-3}\ln\Omega$ [3], compared to the passive scalar transport [2]. This stronger reduction in the transport results from a severe reduction in the amplitude of turbulent velocity in both models. However, the cross-phase is only modestly reduced, as in the scalar field case [1]. These results are in qualitative agreement with the results from both gyrokinetic and gyrofluid simulations of toroidal ion-temperature gradient turbulence [4], but contradict recent claims in some literature. These results highlight the importance of the detailed properties of the flow in determining the overall transport level. We further discuss the effect of mean shearing on the reduction in the intermittent transport due to coherent structures.

Second, we assess the efficiency of random shearing by zonal flows in transport reduction in a scalar field model [5]. A random zonal flow with a finite correlation time renders decorrelation of two nearby fluid elements less efficient, leading to larger amplitude with a slightly different scaling compared to the coherent shearing. In the strong shear limit, the flux is found to have a scaling with the RMS shear Ω_{RMS} as $\propto \Omega_{RMS}^{-1}$. Thus, the effectiveness of zonal shear decorrelation depends on both the strength of the shear and its auto-correlation time.

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