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Unified Scaling Theory for Enstrophy Transfer of Two-Dimensional Turbulent Flows

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Wavenumber dynamics of the enstrophy spectrum in the enstrophy inertial range for a family of two-dimensional flows, so-called α-turbulence, is examined theoretically and numerically. Classical theory[1,2,3] yields the enstrophy spectrum

$$Q(k) \sim k^{-(7-2\alpha)/3} \tag{1}$$

in the enstrophy inertial range. While the theoretical prediction (1) is well agree with the results of direct numerical simulations of forced-dissipated α-turbulence for $0 < \alpha < 2$, it is not supported for $\alpha > 2$. The results of numerical simulations for $\alpha > 2$ exhibit the enstrophy spectrum

$$Q(k) \sim k^{-1}, \tag{2}$$

which is independent of the values of α. Although Pierrehumbert et al.[4] and Schorghofer[5] pointed out the importance of the non-local enstrophy transfer responsible for the failure of (1) for $\alpha > 2$, systematic derivation of (2) based on the enstrophy transfer has been left unsolved problem. Therefore, a unified scaling theory for the enstrophy transfer of α-turbulence, which encompasses all values of α, is proposed in this study. Introducing the non-local enstrophy transfer into the classical theory, a unified scaling law of the enstrophy spectrum in the enstrophy inertial range for α-turbulence is derived. The derived enstrophy spectrum exhibits the transition of scaling form of the enstrophy spectrum between (1) and (2) at α = 2. This result is verified by direct numerical simulations of α-turbulence.

Keywords: two-dimensional turbulence; inertial range scaling; α-turbulence.

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