INTERMITTENCY EFFECTS ON THE UNIVERSALITY OF LOCAL DISSIPATION SCALES IN TURBULENT BOUNDARY LAYER FLOWS WITH AND WITHOUT FREE-STREAM TURBULENCE

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering at the University of Kentucky

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ABSTRACT OF DISSERTATION

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Measurements of the small-scale dissipation statistics of turbulent boundary layer flows with and without free-stream turbulence are reported for $Re_\tau \approx 1000$ ($Re_\theta \approx 2000$). The scaling of the dissipation scale distribution is examined in these two boundary conditions of external wall-bounded flow.

Results demonstrated that the local large-scale Reynolds number based on the measured longitudinal integral length-scale fails to properly normalize the dissipation scale distribution near the wall in these two free-stream conditions, due to the imperfect characterization of the upper bound of the inertial cascade by the integral length-scale. When a length-scale based on Townsend's attached-eddy hypothesis (as suggested by Bailey and Witte, J. Fluid Mech., 2016, vol. 786, pp. 234-252 in channel flow) is utilized to describe the local large-scale Reynolds number near the wall, the description of the Reynolds number scaling was determined to be significantly improved and agreed with that found in homogeneous, isotropic turbulence. However, the scaling based on Townsend's attached-eddy hypothesis agreed best for the lowest 40% of the boundary layer thickness and then it degraded due to the loss of the validity of the attached eddy-hypothesis and the onset of external intermittency.

A surrogate large-scale found from turbulent kinetic energy and mean dissipation rate improved the scaling of the dissipation scales, relative to the measured integral length-scale. The probability density functions of the local dissipation scales were calculated. When the three local large-scale Reynolds numbers are used for normalization, the one based on the longitudinal integral length-scale and the one based on the length-scale of attached-eddy hypothesis provide support for the existence of a universal distribution of the local dissipation scales up to the edge of the outer region of the turbulent boundary layer, which scales differently for inner and outer regions. However, the probability density functions of the local dissipation scales normalized by these two large-scale Reynolds numbers are deviated in interface locations for the flow without free-stream turbulence due to external intermittency.

The surrogate large-scale provided the best agreement throughout the entire depth of the boundary layer. However, in the outer region of the boundary layer, a significantly reduced collapse in the scaled probability density functions was shown due to bias in the calculation introduced by the intermittent presence of laminar flow in the time series. To support that intermittency argument, injection of the free-stream turbulence was determined to improve the distribution of these normalized probability density functions in the intermittency locations for the flow regime without free-stream turbulence.

In addition, unlike in channel flow, in the outer layer of the turbulent boundary layer, the normalized distributions of the local dissipation scales were observed to be dependent on wall-normal position. This was found to be attributable to the presence of external intermittency in the outer layer as the presence of free-stream turbulence was found to restore the scaling behavior by replacing the intermittent laminar flow with turbulent flow.

Thus, the influence of external intermittency on the scaling of the dissipation scale distribution was examined in greater detail for the laminar free-stream condition. Probability density functions of the dissipative scales were compared with, and without, accounting for the external intermittency using an intermittency detection function. Results showed that accounting for the external intermittency produces restores universality in the shapes of the probability density functions at the same wall-normal location at different instances in time. In addition, properly scaling the dissipation-scale-distribution collapses the probability density functions calculated at different wall-normal locations. This improvement in the scaling of the dissipation-scale-distribution supports prior observations of universality of the small-scale description of the turbulence for wall-bounded flow.

KEYWORDS: Turbulence, Turbulent Boundary Layers, Dissipation Scales, External Intermittency, Free-Stream Turbulence

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