THIN SHEAR LAYERS IN HIGH REYNOLDS NUMBER TURBULENCE – DNS RESULTS

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Abstract Data analysis of high resolution DNS of isotropic turbulence with the Taylor micro-scale Reynolds number $R_\lambda = 1131$ on 4096^3 grid points shows that there are significant thin shear layers of thickness of the order of Taylor micro-scale, consisting of a cluster of strong vortex tubes with typical diameter of order 10η (η is the Kolmogorov length scale) . There are big velocity jumps of the order of the rms of the fluctuation velocity across the layers. The locally averaged energy dissipation rate in the layers is much greater than the mean energy dissipation rate, and contributes disproportionately to the overall mean dissipation rate. Up scale and down scale energy transfer to small eddies is largest within and just outside these layers (where the most intense vortices and dissipation occur). The statistics (based on a systematic study) of the layers will be presented and their Reynolds number dependence will be discussed.

INTRODUCTION

Visualization of intense vortices in high Reynolds number (Re) turbulence (the Taylor micro-scale Reynolds number $R_\lambda = 1131$) obtained by the direct numerical simulation (DNS) of forced incompressible Navier-Stokes equations under periodic boundary conditions with 4096^3 grid points [7, 6] showed that strong vortex tubes with typical diameter of order 10η (η is the Kolmogorov length scale) form the large-scale clusters which have very sharp interfaces between high vorticity regions and low vorticity regions in homogeneous isotropic high Re turbulence.[3] Visualization of the intense enstrophy and energy dissipation distributions on a cross section of high Re turbulence suggested that the clusters have layer-like structures. [4] Recently it was also shown that fluctuation of a velocity component along a line in such high Re turbulence exhibits a large jump of the order of the rms values of the velocity across a distance of the order of the Taylor micro-scale. [2]

On the other hand, the analysis of the Reynolds number dependence of one-point velocity gradient statistics shows that the intermittent nature of turbulence becomes stronger with the increase of the Reynolds number. [5] Also, the energy transfer T across the wave number k is highly intermittent and the skewness and flatness of T increase with k in proportion to the powers of kL in the inertial range ($L =$ the integral length scale). [1] The intense down-scale energy transfer regions are close to the intense up-scale energy transfer regions, suggesting that they form large-scale structures of active energy transfer and dissipation regions. These observations suggest that, in high Re turbulence, there exist strong layer-like vortex structures that are the key to the intermittent nature of high Re turbulence. [3]

Recently, we performed detailed conditional analyses near a strong thin shear layer using the DNS data of incompressible homogeneous and isotropic turbulence with 4096^3 grid points in order to elucidate the intermittent nature of high Re turbulence. In this paper, we present a brief summary of the results of the analyses. The statistics (based on a systematic study) of the layers will be presented in the conference. Also, their Reynolds number dependence will be discussed.

CONDITIONAL ANALYSIS NEAR A SIGNIFICANT SHEAR LAYER

High vorticity regions in an active sub-domain whose locally averaged enstrophy is 2.68 times larger than Ω (the enstrophy averaged over the total domain) are shown in Fig.1. The figure demonstrates that strong vortex tubes are confined in a layer-like region that has sharp interfaces at both sides. Following the method used in Ref [9], we determined the left and right interfaces of the layer as the outermost points (x-coordinates) which satisfy $\omega^2/2 > 7.8\Omega$ on the cross section. (The coordinates of the interfaces depend on the threshold value, but its dependence is weak for a certain range of threshold since the interfaces are sharp.)

The results of the conditional analyses of quantities such as enstrophy, rate of energy dissipation, energy transfers and velocity components near the layer are summarized as follows.

1. On both sides of the layer, there are sharp interfaces at which enstrophy as well as rate of energy dissipation changes sharply.
2. The layers' thicknesses ℓ are of the order of the Taylor micro-scale λ. Typically $\ell \sim 4\lambda$, where $\lambda \sim 35L/R_\lambda$.
3. Across the significant layers there are jumps in large-scale velocities of the order of the rms velocity u_o.
4. The locally averaged energy dissipation rate and enstrophy in the layers are much greater than the mean energy dissipation rate and enstrophy, respectively, and contribute disproportionately to the overall mean dissipation rate and

enstrophy.
5. Up scale and down scale energy transfer to small eddies is largest within and just outside these layers (where the most intense vortices and dissipation occur). Here the downscale transfer into the thin layers leads to the very high dissipation within the layers.

Visualization and analysis show the following.
6. The distance between the layers is of the order of the integral length scale.
7. Within the layers, much thinner intermittent, elongated vortical eddies are generated, with microscale thickness $\ell_v \sim 10\eta \sim 178L/R_\lambda^{3/2}$ with associated large peak values of vorticity of order $u_o/\ell_v (< 35\omega_{rms})$ and velocities of the order of $u_o(< 3.4u_o)$, where ω_{rms} is the rms vorticity.
8. The vorticity of these micro-scale eddies have components predominantly parallel to the average vorticity of the thin shear layers. Their spacing is of order lv, so that vortices within the layers are reasonably close packed.
9. The significant thin shear layers play a key role in determining the large scale since the correlation of fluctuations across the layers is small because of the blocking/shear sheltering action of the eddies.

DISCUSSION

Analysis of the 4096^3 DNS data of forced incompressible homogeneous turbulence shows that there are strong thin shear layers in high Reynolds number turbulence. Conditional analysis of a strong thin shear layer shows the structure and properties of the significant layer. Such strong thin shear layers are expected to become prominent when $\ell/L \sim 4\lambda/L \ll 1$ is satisfied at high Reynolds numbers. For the DNS data of turbulence with $R_\lambda = 1131$, $\lambda/L = R_\lambda/Re \sim 0.03$ and $4\lambda/L \sim 0.1$.

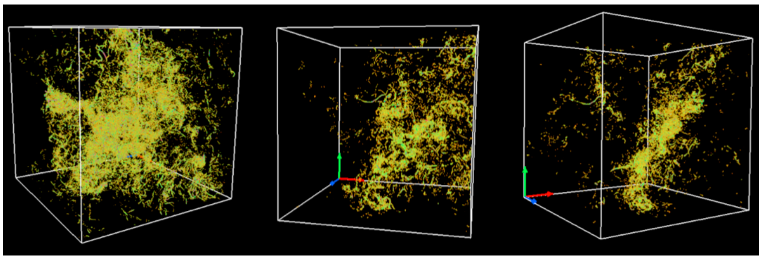

Figure 1. High vorticity regions (from three different view points) in a subdomain with 512^3 grid points. The domain size is approximately $0.72L \approx 32.3\lambda \approx 1542\eta$. x, y, z axes are indicated by red, green, blue arrows, respectively.

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