RELATION BETWEEN ENSTROPHY PRODUCTION AND GEOMETRY NEAR THE TURBULENT/NON-TURBULENT INTERFACE IN FREE SHEAR FLOWS

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Abstract In many free shear flows, such as mixing layers, wakes and jets exhibit a sharp turbulent/non-turbulent interface (TNTI) separating regions of turbulent and non-turbulent or potential flow. In the present work the dependence of enstrophy production on the interface geometry near the TNTI is investigated by using direct numerical simulations (DNS) of a shear free turbulence (SFT) and a temporally developing planar jet (PJET). It is shown that the geometry of the TNTI has impacts on the mechanism governing enstrophy dynamics within the interface layer itself. In particular it is shown that enstrophy production within the turbulent sublayer is primarily associated with a convex shape of the interface both the SFT and PJET.

INTRODUCTION

Turbulent/nonturbulent interfaces (TNTI) separate turbulent and nonturbulent regions in many free shear flows such as wakes, jets and mixing layers [1]. The TNTI is a layer with finite thickness, which consists of the turbulent sublayer (TSL) and the viscous superlayer (VSL): in the VSL vorticity is transported from the turbulent into the irrotational region by viscous diffusion, whereas inviscid vortex stretching governs the enstrophy generation within the TSL. The TNTI has a convoluted surface, and its convolutions are related to large vorticity structures from the turbulent region underneath. In this study, direct numerical simulations (DNS) of a shear-free turbulence (SFT) and a temporally developing planar jet (PJET) are performed for investigating the relationship between the interface geometry and the enstrophy production within the TSL. We use the mean curvature of the vorticity magnitude iso-surfaces for characterizing the interface geometry.

DNS OF SHEAR FREE TURBULENCE AND PLANAR TURBULENT JETS

The TNTI is investigated in shear free turbulence SFT [3] and PJET [2] by using DNS, which have been detailed in previous works [2, 3], and therefore only a short description is given here. In the SFT, the computational domain, whose size is $2\pi \times 2\pi \times 2\pi$, uses $(512 \times 512 \times 512)$ collocation points and the initial field consists of homogeneous isotropic turbulence ($|y| \leq 0.7\pi$) and the non-turbulent flow has zero velocity ($0.7\pi \leq |y| \leq \pi$). The turbulent flow spreads into the non-turbulent flow with time in the absence of mean shear. The Taylor Reynolds number is $Re_\lambda = u_{\mathrm{rms}}\lambda_x/\nu = 100$ at the center of the turbulent core region (u_{rms}: rms velocity, λ_x: Taylor microscale, and ν: kinematic viscosity). The PJET is carried out in a computational domain with sizes $L_x = 7.5h$, $L_y = 10h$ and $L_z = 7.5h$ in the streamwise (x), lateral (y) and spanwise (z) directions, respectively, where h is the inlet nozzle width of the jet, and the number of grid points is $(N_x \times N_y \times N_z) = (768 \times 1,024 \times 768)$. The Reynolds number is $Re = U_1 h/\nu = 6,000$ (U_1: initial mean streamwise velocity at the jet centerline $y = 0$). The Taylor Reynolds number is $Re_\lambda = 98$ on the jet centerline.

RESULTS

An isosurface of fixed vorticity magnitude $|\boldsymbol{\omega}| = \omega_{\mathrm{th}}$ is used for investigating the TNTI, where the detection threshold ω_{th} is determined from the relationship between ω_{th} and the turbulent volume [1] so that the iso-surface of $|\boldsymbol{\omega}|$ is at the outer edge of the TNTI layer. We define this particular iso-surface as the *irrotational boundary* and conditional statistics are calculated in respect to the distance (denoted y_{I}) to this particular boundary as represented in Fig. 1(a).
We investigate the large-scale geometry of the TNTI by using the large-scale mean curvature defined by $H \equiv -\nabla \cdot \boldsymbol{n}_{\mathrm{LS}}$, where $\boldsymbol{n}_{\mathrm{LS}} \equiv -\nabla\overline{\omega^2}/|\nabla\overline{\omega^2}|$ and $\overline{\omega^2}$ is a low-pass-filtered value of ω^2 used to remove small scale feature from the TNTI. We used a top-hat filter with a filter width of 0.5λ, where $\lambda = (\lambda_x + \lambda_y + \lambda_z)/3$ at $y = 0$. A concave shape is represented by positive H while negative H represents a convex shape (Fig. 1(a)). Figure 1(b) shows the irrotational boundary in the PJET with the colors representing H/λ. Figure 1(c) shows the probability density function (pdf) of H in SFT and PJET. In both flows, a peak of the pdf appears for $H < 0$ (convex) while the pdf is positively skewed in agreement with [4]. Figure 1(b) also shows that a large part of surface area has slightly negative values of H although large positive H appears on thin lines. Figure 2 shows the conditional joint pdf of H and enstrophy production $P_\omega = \omega_i S_{ij} \omega_j$, ($S_{ij}$, is the strain-rate tensor) within the TSL at $y_{\mathrm{I}}/\lambda = -0.25$, for SFT and PJET. Positive and negative enstrophy production tends to be more important for convex shapes ($H < 0$), although P_ω can be locally important also for a concave shapes ($H > 0$) provided H is small. Moreover, P_ω is close to zero for very large negative/positive H, which are often observed

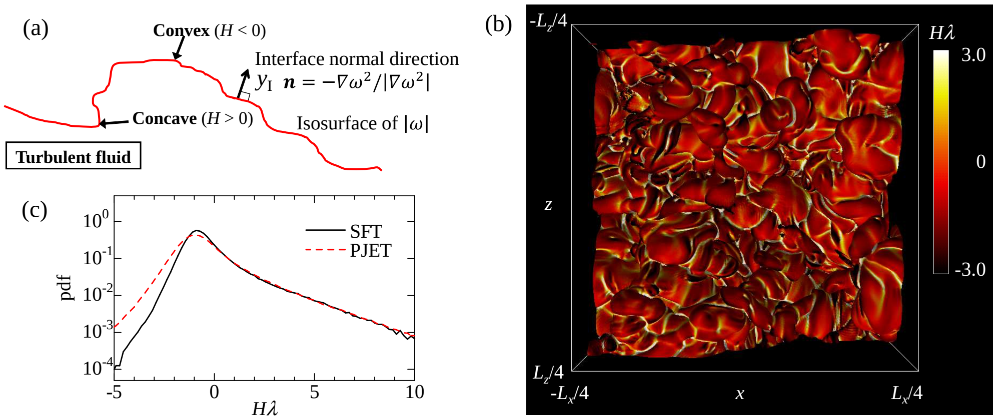

Figure 1. (a) Definition of the distance from the irrotational boundary y_I exhibiting regions of both concave ($H > 0$) and convex ($H < 0$) shape. (b) Visualization of the irrotational boundary in the PJET. The color of the irrotational boundary shows large-scale mean curvature $H \equiv -\nabla \cdot \boldsymbol{n}_\mathrm{LS}$ normalized by the Taylor microscale $\lambda = (\lambda_x + \lambda_y + \lambda_z)/3$ at $y = 0$. (c) Pdf of large-scale mean curvature H of the irrotational boundary in SFT and PJET.

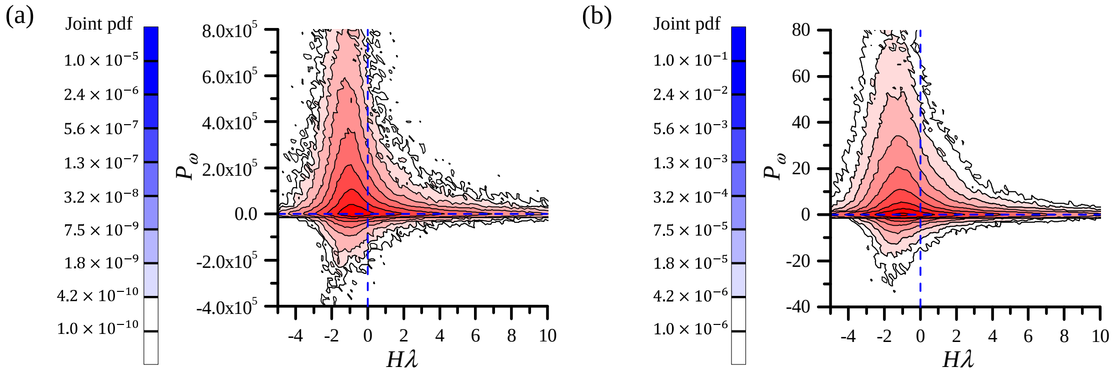

Figure 2. Conditional joint pdf of large-scale mean curvature H and enstrophy production $P_\omega = \omega_i S_{ij} \omega_j$ within the TSL at $y_\mathrm{I}/\lambda = -0.25$ in the SFT (a) and PJET (b).

between the large-scale vortical structures as in Fig. 1(b). It is noteworthy that the shape of these pdfs is very similar for the SFT and PJET suggesting that the mean shear and large-scale inhomogeneities do not affect the enstrophy production mechanism. Future work will focus on the detail analysis on the effects of the enstrophy governing mechanism across the entire TNTI layer, and on the effects of freestream turbulence on these mechanisms.

CONCLUSION

The relationship between the enstrophy production and the mean curvature of the irrotational boundary is investigated inside the TSL within the TNTI layer in shear free turbulence and turbulent planar jets. The large-scale mean curvature shows that a large part of the interface area is characterized by a convex shape, while a concave shape appears only on small (thin) lines. It is shown that the enstrophy production is larger in regions with a convex shape, and the observed dependence of enstrophy production on the large-scale mean curvature is very similar both in SFT and PJET.

References

[1] C. B. da Silva, J. C. R. Hunt, I. Eames, and J. Westerweel. Interfacial layers between regions of different turbulence intensity. *Annu. Rev. Fluid Mech.*, **46**:567–590, 2014.
[2] C. B. da Silva and J. C. F. Pereira. Invariants of the velocity-gradient, rate-of-strain, and rate-of-rotation tensors across the turbulent/nonturbulent interface in jets. *Phys. Fluids*, **20**(5):055101, 2008.
[3] M. A. C. Teixeira and C. B. da Silva. Turbulence dynamics near a turbulent/non-turbulent interface. *J. Fluid Mech.*, **695**:257–287, 2012.
[4] M. Wolf, M. Holzner, B. Lüthi, D. Krug, W. Kinzelbach, and A. Tsinober. Effects of mean shear on the local turbulent entrainment process. *J. Fluid Mech.*, **731**:95–116, 2013.