THE TURBULENT/NON-TURBULENT INTERFACE AND VISCOUS SUPERLAYER IN TURBULENT PLANAR JETS

Carlos B. da Silva & Rodrigo R. Taveira
IDMEC/IST, Mecânica I, 1^o andar/LASEF, Av. Rovisco Pais, 1049-001 Lisbon, Portugal.

Abstract Direct numerical simulations of turbulent planar jets are used to study the characteristics of the turbulent/non-turbulent interface (TNTI) separating the turbulent from the irrotational regions of the jet, and to define and visualize the viscous super-layer. Conditional statistics near the TNTI show the existence of a region of a region of "dominating enstrophy diffusion and negligible enstrophy production", outside the TNTI. This is the much debated viscous super-layer. The super layer is not continuos and its thickness is of the order of the Kolmogorov micro-scale.

INTRODUCTION

Turbulent entrainment (TE) is a key mechanism occurring in a variety of shear flows *e.g.* mixing layers, wakes and jets, and also in boundary layers since it governs important exchanges of mass, momentum and passive or active scalar quantities across a thin boundary separating turbulent (T) from the irrotational (or non-turbulent - NT) flow region: the so called turbulent/nonturbulent (T/NT) interface[1]. Detailed analysis of this T/NT interface is crucial if one is to understand exactly what the entrainment mechanism consists of, since it has been shown in recent works that TE is primarily associated with small scale ("nibbling") eddy motions taking place in the entire interface region[2] and not with "engulfing" induced by large scale vortices.

A long standing problem concerns the existence of a viscous superlayer outside the T/NT interface, where vorticity from the interior of the turbulent flow region can be communicated into the surrounding irrotational flow through a mechanism of vorticity viscous diffusion. In contrast with the T/NT interface, for which some information *e.g.* regarding its scales already exists[3], few information regarding even the existence of this viscous superlayer exists. For instance, even the simple observation of this viscous superlayer has been elusive[2] and very few of its characteristics are know *e.g.* what is its mean thickness and whether the superlayer is continuous or somehow connected with (or imposed by) the range of eddy structures existing inside the shear layer. It is important to stress that the viscous superlayer is not to be confused with the T/NT interface, which is a surface associated with a strong enstrophy gradient observed near the jet edges. The viscous superlayer, whatever its exact definition, must lay outside the T/NT interface since the flow inside the shear layer (after crossing the T/NT interface) is dominated by an intensification of small scale turbulence which turn quickly the enstrophy production the dominating mechanism once the T/NT interface is crossed.

RESULTS

The present work uses direct numerical simulations (DNS) of turbulent plane jets and shear free turbulence are used to study the characteristics of the T/NT interface and of the viscous superlayer[3]. Specifically we analyse the statistics of the (local) thickness and length of these two layers as well as their relation with the presence of tube and sheet like structures, and the scalar interface, and with the local nature of the T/NT interface *i.e.* convex or concave curvature. Figures 1 (a) and (b) show a detail of one of the DNS used in this work and of the geometry of the T/NT interface, respectively.

Detailed analysis of the local thickness of the T/NT interface δ_ω shows that in jets and in shear free turbulence the mean thickness is $\delta_\omega \sim \lambda$ and $\delta_\omega \sim \eta$, respectively. However the local value of δ_ω changes considerably in these flows *e.g.* figure 1 shows the probability density function (pdf) of δ_ω in a jet. As can be seen a plateau exists from about $3\eta < \delta_\omega < 6\eta$ showing the imprint of the intense vorticity structures in the definition of the T/NT interface in jets[4].

If one defines, as originally postulated by Corsin and Kistler[1], that the viscous superlayer is a region of "dominating enstrophy diffusion and negligible enstrophy production" one can 'see' that such a layer does exist. A conditional profile of the enstrophy budget as a function of the distance from the T/NT interface allows one to see the 'mean' superlayer thickness (Fig. 1 d). This layer is however completely outside the T/NT interface (and is not part of it as the original sketches from Corsin and Kistler[1] seem to imply). The superlayer is not continuos and seems to be continuous only around half circular stretches of fluid with mean length of the order of the Taylor micro-scale in jets. In contrast to what happens for the T/NT interface, the local thickness of the superlayer δ_ν is of the order of the Kolmogorov micro scale $\delta_\nu \sim \eta$ be it in either jets or shear free turbulence (T/NT interface without mean shear). This layer can only be observed in extremely fine DNS which maybe explains why it was so difficult to see before.

The present results open the way to the analysis of the scalar T/NT interface and suggest the existence of a scalar superlayer, with implications for studies of mixing mechanism in turbulent reactive flows.

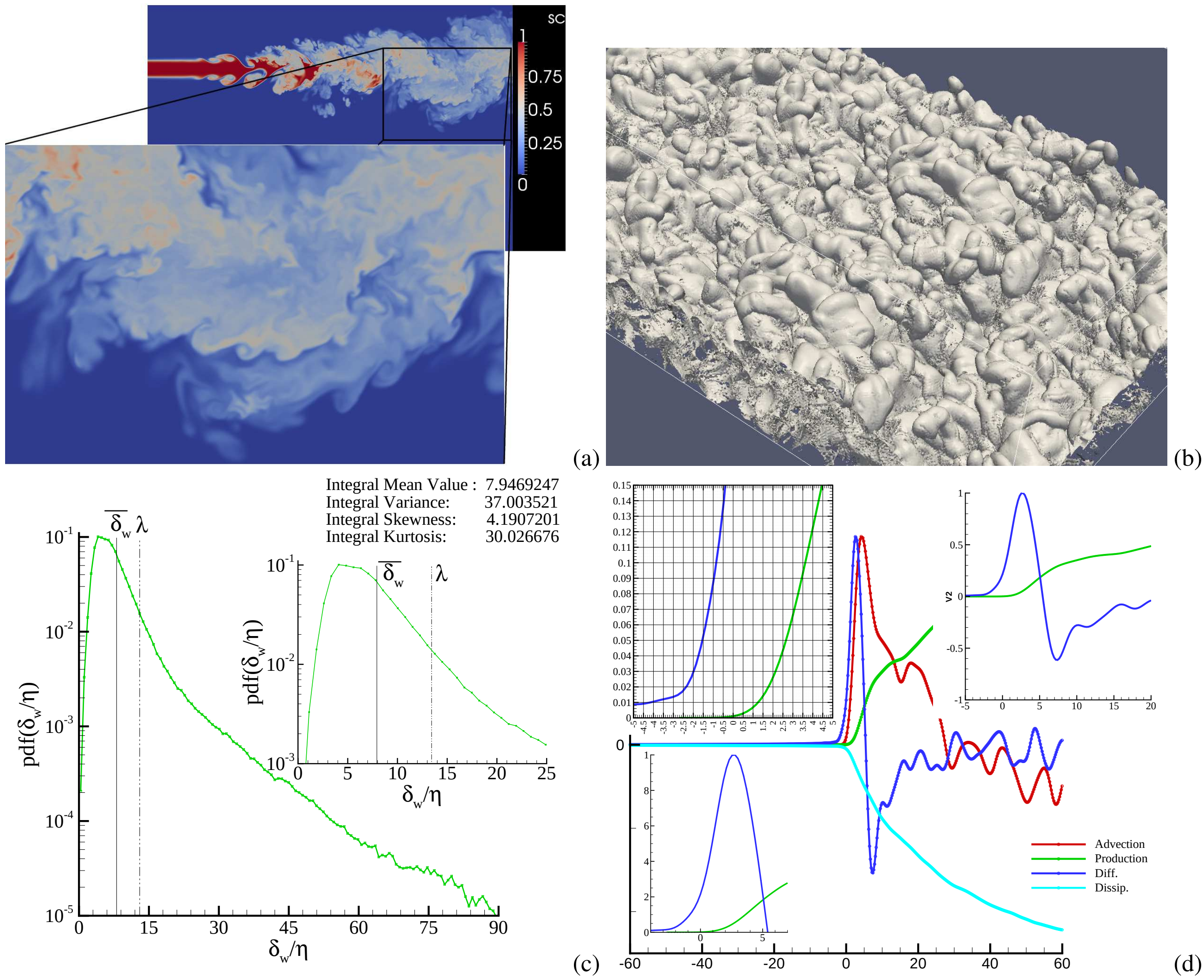

Figure 1. (a) Side view of scalar contours in one of the DNS of turbulent planar jets used in the present work; (b) Detail of the Turbulent/non-turbulent interface defines through iso-surfaces of vorticity corresponding to the detection thteshold in the turbulent planar jet; (c) Probability density function (pdf) of the local T/NT interface thickness for the turbulent planar jet; (c) Conditional mean profiles (in relation to the distance from the T/NT interface) of the enstrophy transport equation (advection, production, viscous diffusion, and viscous dissipation). The horizontal axis (x) represents the distance from the T/NT interface which is at $x = 0$. $x < 0$ is the irrotational region while $x > 0$ is the turbulent region (distances are normalised by the Kolmogorov micro-scale).

References

[1] S. Corrsin and A. L. Kistler. Free-stream boundaries of turbulent flows. Technical Report TN-1244, NACA, 1955.

[2] J. Westerweel, C. Fukushima, J. M. Pedersen, and J. C. R. Hunt. Mechanics of the turbulent-nonturbulent interface of a jet. *Phys. Review Lett.*, 95:174501, 2005.

[3] C. B. da Silva and R. R. Taveira. The thickness of the turbulent/nonturbulent interface is equal to the radius of the large vorticity structures near the edge of the shear layer. *Phys. Fluids*, **22**, 121702, 2010.

[4] C. B. da Silva, R. N. dos Reis 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. *J. Fluid Mechanics*, 685:165–190, 2011.

[5] M. C. Teixeira and C. B. da Silva. Turbulence dynamics near a turbulent/non-turbulent interface. *J. Fluid Mechanics*, 695:257–287, 2012.