SCALAR MIXING AT TURBULENT/NON-TURBULENT INTERFACE OF A TURBULENT PLANE JET

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ABSTRACT

The interface region that bounds fully developed turbulent shear flow from the vortical non-vortical regions in free shear flows is a long-standing issue in turbulence research. Understanding the local dynamics that take place at such interfacial layer are key to the study of turbulent mixing and entrainment. Dimotakis (2005) highlights the importance of studying the mixing process of a passive scalar in a wide range of engineering applications, *e.g.* combustion. Recent investigations on the topic focused in the analysis of the properties of both the T/NT interface, particularly in the vorticity structures close to the T/NT interface. da Silva & Taveira (2010) and Reis *et al.* (2011) investigated these structures showing that the T/NT interface is made of these turbulent structures. Moreover, Reis *et al.* (2011) and Taveira & da Silva (2013) studied the role of vorticity structures in the enstrophy and kinetic energy transport across the T/NT interface, respectively. The present study aims to explain the dynamics of the turbulent mixing of a passive scalar through the study of scalar gradient and fluctuations transport mechanisms. It is also investigated the topology of the scalar gradient structures, which are responsible for the transport of scalar fluctuations. The present study aims to explain the dynamics of the turbulent mixing of a passive scalar through the study of scalar gradient and fluctuations transport mechanisms. It is also investigated the topology of the scalar gradient structures, which are responsible for the transport of scalar fluctuations. The present work uses data from a single direct numerical simulation of a turbulent plane jet at Reynolds number of $Re = 140$ and the Schmidt number is 0.7. Structure tracking and conditional statistics are employed allowing to filter out intermittence and a clear perspective of the local dynamics. The instantaneous fields showed that the passive scalar field is mainly arranged in intense scalar gradient sheets that are found along regions of persistent strain, in particular at the T/NT interface. However at the moderate Reynolds number these sheets are not flat as reported in literature, and are seldom arranged parallely. The jump in the mean conditional scalar as width of the order of the Taylor scale, in agreement with Westerweel *et al.* (2009). Conversely, the jump in the scalar gradient conditional profile suggests the sheet structures to have an average width of the order of the Kolmogorov scale. The topological analysis of the structures shows that on average the intense scalar gradient sheets have a thickness of $\approx 3\eta$ and a length of $\approx 2\lambda$. The conditional analysis of the scalar gradient and variance transport revealed that the mixing is taking place particularly close to the T/NT interface, over a region with a thickness of $\approx 12-15\eta$.

Introduction

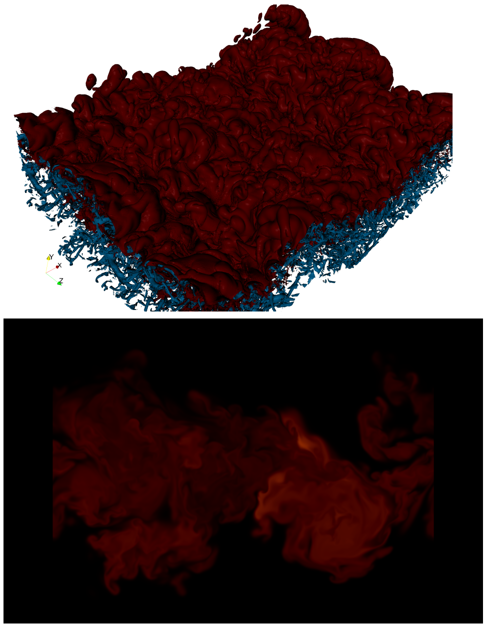
In free shear flows, such as jets, sharp and intricate layers separate the irrotational region from the turbulent flow core. These layers establish an interface region - the T/NT interface - across which the exchanges of mass, energy and momentum, that allow the shear layer to grow and develop naturally, take place. A large effort has been made, in the near past, in order to improve the understanding of the local dynamics that take place at such interfacial region. The experiments of Westerweel *et al.* (2005) hinted that the main entrainment mechanism is nibbling taking place at the smallest scales, rather than engulfing events driven by large scale of the mean flow (Dimotakis (2005)). The analysis of the geometric properties of both the T/NT interface and its neighbor vorticity structures has shown that the interface is made of these turbulent structures, whose radius is seen to be of the order of the Taylor micro-scale in the case of shear flows (da Silva & Taveira (2010)). Reis *et al.* (2011) studied, in depth, the role of the intense vorticity structures (IVS), at the T/NT interface, obtaining results that supported the conclusions previously obtained (da Silva & Taveira (2010)). The developments in the methods used to study the local dynamics also allowed a detailed study of the mixing processes taking place between the turbulent and irrotational regions of the flow. For instance, the conditional analysis of the kinetic energy transport in Taveira & da Silva (2013) showed that non-viscous mechanisms play a central role in the entrainment process. Numerous studies showed that chemical reactive flows can be quite satisfactorily modelled using flamelet models, where a thin reaction zone and sufficiently fast chemistry are assumed (Pitsch (1998)). This models assume flames to be an ensemble of laminar flames, where the thermochemical properties can be described as a function of a passive scalar, or set of scalars, whose transport equations have to be resolved. Namely, the simplest models describe such properties as a function of the mixture fraction that can be treated as a passive scalar. Therefore the understanding of a passive scalar field plays a major role in recent combustion efforts. Particularly, the correct prediction of the transport and dissipation of scalar gradient sheets (and scalar fluctuations) is of the upmost importance as any error in their prediction may lead to very large errors in combustion predictions using the flamelet model (Pitsch *et al.* (2000)). Moreover, taking into account not only the average value but also the scalar fluctuations of the mixture fraction (passive scalar variance) allows LES for more accurate predictions of combustion, in particular for secondary species of interest for pollutant dispersion analysis (Pitsch (1998)). The present work focuses on the study of the dynamics governing the mixing of a passive scalar across the T/NT interface, important for subjects such as pollutant dispersion and combustion. One proposes to accomplish this by means of a conditional analysis of scalar gradient and fluctuations transport mechanisms. The study also aims to investigate the topological properties of the scalar field structures, responsible for the different transport of scalar fluctuations.

NUMERICAL METHOD

The present work makes use of a direct numerical simulation of a turbulent plane jet at a Reynolds number of $Re\lambda = 140$ (Fig. 1), and the Schmidt number is 0.7. This DNS has been used previouslydetails can be found at da Silva & Taveira (2010). and its Specifically, we analyze the local properties of the scalar interface and establish a comparison with the T/NT interface defined by the vorticity field. An extensive set of conditional statistics in relation to the distance to the scalar and T/NT interfaces is used to shed light on the ruling mechanisms in the scalar gradient (therein scalar dissipation) and scalar variance (fluctuations intensity) transport equations. Further details on th methodology can be found at da Silva (2009) and Taveira & da Silva (2013). In order to study the scalar gradient and variance dynamics one computed and analyzed all the mechanisms of transport equations scalar gradient (Eq. 1) and variance (Eq. 2).

$$\frac{\partial}{\partial t}\left(\frac{1}{2}G_iG_i\right)+u_j\frac{\partial}{\partial x_j}\left(\frac{1}{2}G_iG_i\right)=-G_iG_jS_{ij} -\kappa\left(\frac{\partial G_i}{\partial x_j}\right)^2+\kappa\frac{\partial^2}{\partial x_j^2}\left(\frac{1}{2}G_iG_i\right) \tag{1}$$

$$\frac{\partial}{\partial t}\left\langle\frac{1}{2}\theta'\theta'\right\rangle+\langle u_j\rangle\frac{\partial\left\langle\theta'\theta'\right\rangle}{\partial x_j}=\kappa\frac{\partial^2\left\langle\theta'\theta'\right\rangle}{\partial x_j^2}+ 2\kappa\left(\frac{\partial\left\langle\theta'\right\rangle}{\partial x_j}\right)^2-2\kappa\left\langle\frac{\partial\theta'}{\partial x_j}\frac{\partial\theta'}{\partial x_j}\right\rangle \tag{2}$$



(a)

(b)

Figure 1. (a) Visualization of the T/NT interface (red) and Intense Vorticity Structures, IVS, (blue). (b) Visualization of the scalar field at the jet central plane.

Additionally the topological properties of the scalar sheet structures are analyzed using a procedure that tracks the sheets centre plane. This simple procedure starts by identifying a given subset of the scalar gradient field (30% of the total turbulent volume). Subsequently from the agglomerate of structures a set of individual sheets is computed using of local thresholds. This allows the tracking of the sheet centre planes (centerlines in 2D) and consequently the computations of the thickness and length of the entire set of structures.

RESULTS AND DISCUSSION

The conditional profiles of the mean scalar field, $\langle\theta\rangle_I$, and scalar variance, $\left\langle\theta'^2\right\rangle_I$, as function of the distance from the T/NT interface are shown in figures and , respectively. At the *scalar interface* the observed jump, in the scalar averaged profile, is quite stronger than the one observed for the velocity field, however both have a width of the order of the Taylor Scale. Figure also shows that conditional statistics relative to the T/NT and scalar interfaces are qualitatively and quantitatively similar, despite a small offset of a couple Kolmogorov Scales. Such offset can be explained by a faster scalar diffusive spread than vorticity, for $Sc < 1$, which means that the scalar interface is outside the turbulent region.

For the scalar gradient the observed jump, fig. , has a thickness of the order of the Kolmogorov scale. It is also clear that this jump is wider and its limits harder to define when using statistics conditioned to the distance from the T/NT interface than when using the ones conditioned to the distance from the scalar interface. In the latter it is clear that the jump has a width of $\approx 7-8\eta$. Figure shows the conditional profile of the scalar gradient, where the distance from the interface is non-dimensionalized by a scalar Taylor scale, $\lambda_\theta = \left[(\theta'^2)/(\partial\theta'/\partial x)^2\right]^{1/2}$. When using either its value at the scalar interface or at the jet core, the width

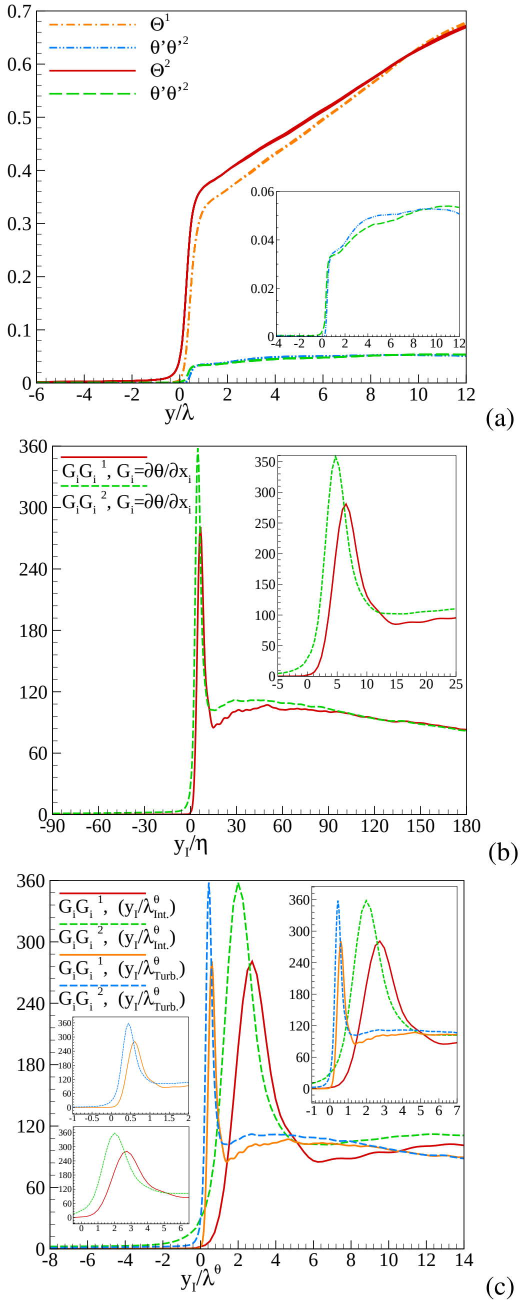


Figure 2. (a) Conditional profile of mean scalar and scalar variance. (b) Conditional profile of scalar gradient norm (zoom shows Kolmogorov scale). (c) Conditional profile of scalar gradient norm (with y_I non-dimensionalized by the Taylor scale). Note: Conditional distance to the *scalar interface*[1] and to the T/NT interface[2].

of the jump is of the order of λ_θ. Instantaneous fields and local profiles (figs. and) show evidences of a continuous *scalar interface* made of intense gradient (intense scalar dissipation) sheets wrapped around the structures defining the T/NT interface. Moreover, local profiles show that the thickness of these sheets and therefore of the scalar interface is of the order of a few Kolmogorov scales. From the tracking procedure employed the figures for the scalar thickness and length are $\approx 3\eta$ and $\approx 5\lambda$, respectively.

The scalar gradient and variance transport equations were also investigated to study the ruling mechanisms of scalar mixing at the edge of the jet. Figure shows that all

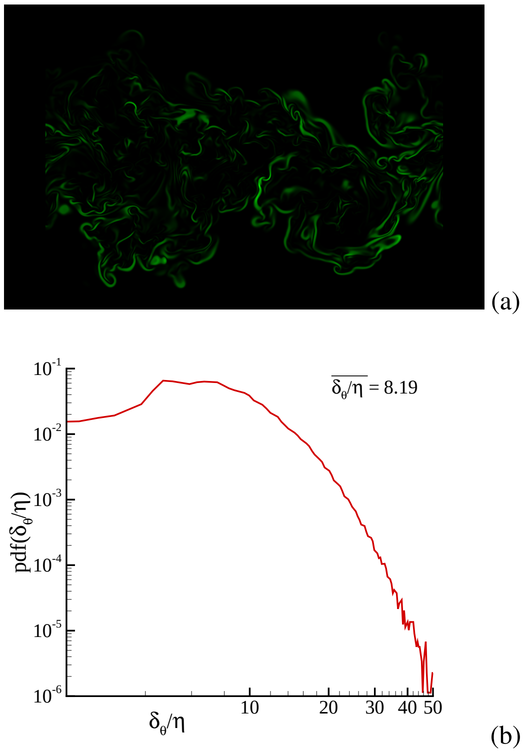


Figure 3. (a) Visualization of scalar gradient sheets at the jet central plane. (b) Pdf of the "scalar interface" thickness.

mechanisms are more important close to the interface and that at the turbulent core the scalar gradient budget reduces itself to an almost perfect balance between production and dissipation. Comparing the conditional results in relation to the T/NT and scalar interfaces one observes similar evolutions and a reasonable agreement in the acting width, however the levels obtained vary at some extent. At the interface vicinity, molecular diffusion takes an important role, from $-1y_I/\eta$ to $5y_I/\eta$, diffusing gradients from the production (higher strain) region towards the interface, softening the strong inhomogeneities that exist at the scalar interface. However advection still is the local dominant mechanism in the scalar gradient transport. The transport mechanisms are also the ones responsible for the growth in the scalar variance to entrained fluid, despite turbulent diffusion playing the dominant role close to the interface, smoothing scalar (up to and boosting scalar levels as far as $-5y_I/\eta$. Within the turbulent core, production and dissipation maintain the expected balance, but near the interface dissipation displays a negative peak close to the width of the scalar interface. From this location inwards, production assumes the dominant role, until a distance from the T/NT interface of the order of λ. The results observed suggest that the mixing of the scalar fluctuations takes place at very small scales, posing challenges for the modelling of sub-grid in the context of LES, as suggested by da Silva (2009).

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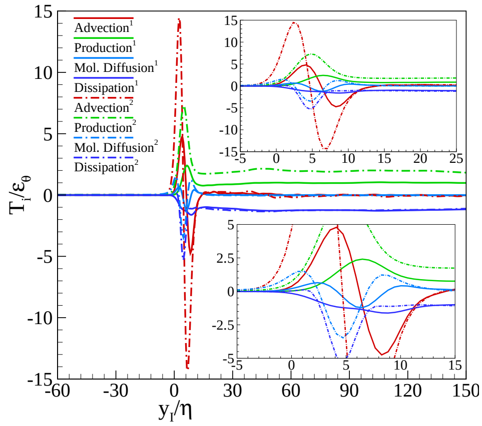
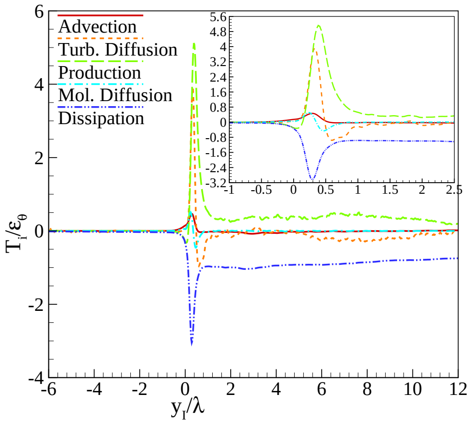


(a)



(b)

Figure 4. (a) Conditional profiles of the scalar gradient transport equation. (a) Conditional profiles of the scalar variance transport equation.

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