THE TURBULENT/NON-TURBULENT INTERFACE IN A TEMPORALLY EVOLVING MIXING LAYER

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Abstract Based on DNS of a temporally evolving mixing layer, we investigate statistics of the turbulent/non-turbulent (T/NT) interface layer. We use scalar gradient trajectories to study the local structure of the turbulent scalar field. Based on these trajectories, we partition the scalar field into three regions, namely a fully turbulent region, an outer flow and the T/NT interface, according to an approach developed by [8]. Based on these different regions, we investigate in a next step zonal statistics of the scalar pdf $P(Z)$ as well as the scalar difference along the trajectory ΔZ and its mean scalar value Z_m.

ANALYSIS

Turbulence tends to be created locally where the flow is most unstable, which can be observed for instance in jet flows, wakes and boundary layers, cf. [1, 10]. In these examples turbulent regions are located adjacent to non-turbulent (NT) ones, where no turbulence is generated. [2] first termed the layer separating the turbulent from the NT region as the 'laminar superlayer'. [1] note that irrotational velocity fluctuations are usually found in the non-turbulent flow outside the interface layer, which does not mark an absence of velocity fluctuations but a change in the character of the fluctuations from vortical to irrotational. Vorticity is transmitted to fluid through the action of molecular viscosity, so that there must exist a shear layer that is essentially viscous in nature, across which all major changes between outer fluid and the fully turbulent interior fluid take place, including those of a transported scalar.

The question arises how the local topology of these flows may be described from a structural point of view and how their impact may be described physically and quantified in terms of turbulence statistics. [10] used a random collection of coherent large-scale eddies to describe first and second order statistics in axisymmetric jets and wakes. [7, 11] suggest that small-scale eddy motions (nibbling) acting on the T/NT interface layer are the dominant physical mechanism.

These nibbling eddies are of major importance for the dynamics of the interface layer. Detailed spatial analyses of this region have recently been made experimentally (e.g. [11]) and numerically (e.g. [3]), giving deeper insight into the vorticity dynamics close to the T/NT interface layer. In addition, [12] examined the temperature field of a non-isothermal jet and observed good agreement of the statistics with those obtained from investigations of concentration and axial momentum [11, 3]. Furthermore, [3] argue, based on scaling arguments involving the viscosity and the rate of strain that in the presence of a mean shear, the characteristic length scale δ associated with the thickness of the interface layer scales with the Taylor microscale λ.

In a previous work, cf. [4], the contribution of the T/NT interface layer to the mixture fraction probability density function (pdf) P(Z) at various axial and radial locations has been examined and it was concluded that the T/NT interface and its contributions to the mixture fraction pdf are of major importance particularly in the early part of the jet. In addition, the scaling of the thickness δ of the scalar T/NT interface layer was analyzed at Reynolds numbers $Re_\lambda = 60 - 140$, where Re_λ denotes the local Reynolds number based on the Taylor scale λ, using the mixture fraction profile in interface normal direction. It was observed that $\delta/L \propto Re_\lambda^{-1}$, where L is an integral length scale, meaning that $\delta \propto \lambda$.

The region of the T/NT interface layer was recently further analyzed by [8], who investigated the DNS of a temporally evolving shear layer using gradient trajectories. Based on these gradient trajectories, they partition the scalar field into a fully turbulent zone, a zone containing the T/NT interface layer and the outer laminar flow. Based on the different regions, they examine the probability of these three zones at different locations in the shear layer and investigate the scalar probability density function and the conditional scalar dissipation rate in the zones in the presence of external intermittency. This approach was adopted by [5], where zonal statistics of the scalar pdf $P(Z)$ as well as the scalar difference along a scalar gradient trajectory ΔZ and its mean scalar value Z_m were examined based on experimentally obtained scalar fields in a jet flow.

In the present study the T/NT interface layer is investigated in a direct numerical simulation (DNS) of a temporally evolving mixing layer using standard statistics such as the pdf of the interface location that are compared to the results of previous studies, cf. [8]. Afterwards, we use scalar gradient trajectories to determine the locations of the fully turbulent region, the outer flow and the T/NT interface layer an examine zonal statistics of the mixture fraction pdf.

DNS

The DNS is performed by solving the non-dimensional unsteady incompressible Navier-Stokes equations, given by Eq. 1. Additionally an advection diffusion equation is solved for a passive scalar with unity Schmidt number.

$$\frac{\partial u_i^*}{\partial t^*} = -\frac{\partial}{\partial u_j^*}(u_i^* u_j^*) + \frac{1}{Re}\frac{\partial^2 u_i^*}{\partial x_j^{*2}} - \frac{\partial p^*}{\partial x_i^*} \tag{1}$$

The non-dimensional Navier-Stokes equations are solved using the velocity difference ΔU between the upper and the lower boundary $\Delta U = u_1(y = L_y) - u_1(y = 0)$ and the vorticity thickness $\delta_{\omega,0}$ for non-dimensionalization. The initial vorticity thickness is given by Eq. 2. Non-dimensional parameters are labeled by an asterisk.

$$\delta_{\omega,0} = \delta_\omega(t = 0) = \left.\frac{\Delta U}{\left(d\langle u_1^*\rangle / dz^*\right)_{max}}\right|_{t=0} \tag{2}$$

The velocity profile is initialized according to [9] and is obtained by Eq. 3.

$$\langle u_1(y)\rangle = \frac{\Delta U}{2}\tanh\left(\frac{-y}{2\delta_{\omega,0}}\right),\ \langle u_2(y)\rangle = \langle u_3(y)\rangle = 0 \tag{3}$$

In the present simulation spatial derivatives are calculated by a sixth-order finite difference compact scheme. The scheme is introduced in [6]. The temporal integration is performed using a fourth-order Runge-Kutta-method.
A Poisson equation is transformed by Fourier transformation into a Helmholtz equation supplying a solution for the closing problem. The initial velocity profile mentioned before is superposed by a broadband random Gaussian velocity field derived from a one-dimensional turbulent energy spectrum to facilitate laminar-turbulent transition. This energy spectrum is proportional to $\kappa^2 \exp\left(\frac{\kappa}{\kappa_0}\right)$, with κ being the wavenumber with a peak at the wavelength $\kappa_0 = 3\delta_{\omega,0}$ comparable to the energy spectrum imposed by [8]. The initial turbulence intensity is set to 6%. The initial Reynolds number $Re_{\delta,0} = \Delta u \delta_{\omega,0}/\nu$, based on the voritcity thickness, is set to 500. The streamwise and the spanwise boundary conditions are periodic. The crosswise boundaries are determined by the free-slip condition, imposing a zero-gradient $(\partial/\partial y)|_{y=\pm L_y/2} = 0$ to each quantity. Furthermore an impermeability condition is imposed to the crosswise boundary to assure conservation of mass. Boundary conditions for the scalar values are one at the upper boundary and zero at the lower boundary respectively.

Table 1. Simulation parameters

t^*	Re_λ	λ^*	δ_m^*	δ_ω^*	Re_δ	η	$\eta/\Delta x$	ℓ_m	g_m
44	80.91	0.25	0.6632	3.6	982	0.0144	0.63	0.497	0.821
110	138.38	0.41	1.43	7.00	2887	0.0175	0.76	0.623	0.518
179	202.16	0.56	2.41	11.26	6130	0.0199	0.86	0.707	0.387

The size of the computational domain is given by $L_x = 30\pi$, $L_y = 43$ and $L_z = 15\pi$. For an appropriate resolution of the shear layer, the grid is equidistant ($\Delta x = \Delta y = \Delta z$) in the core region (between $0.25L_y$ and $0.75L_y$). Grid spacing is coarsening towards the crosswise boundaries using a polynomial function of the order three. Grid spacing in streamwise and spanwise direction is constant over the complete domain. The domain is discretized by $4096 \times 1536 \times 2048$ ($N_x \times N_y \times N_z$). The resolution in the core region is given by $\Delta x \leq 1.82\eta$ with the Kolmogorov size $\eta = \nu^{3/4}\varepsilon^{-1/4}$, supplying detailed information about the small-scale turbulence in the mixing layer, see Tab. 1 for details.

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