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14TH EUROPEAN TURBULENCE CONFERENCE, 1–4 SEPTEMBER 2013, LYON, FRANCE

DIRECT SIMULATION OF TURBULENT ENTRAINMENT IN A TEMPORAL PLANE JET

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Abstract We report on properties of the viscous superlayer using direct simulation of a temporal plane jet at *Re* $= 2500$. The local entrainment velocity v_n scales with the Kolmogorov velocity with a prefactor that depends on the enstrophy threshold. The entrainment flux $v_n S$ is practically independent of the threshold choice, as is observed from the mean entrainment velocity $u_e = v_n S/A$, where S is the enstrophy isosurface area and A is the surface area after projecting onto the homogeneous directions. A decomposition of v_n into a mean and turbulent contribution indicates that turbulent fluctuations are the dominant mechanism by which the interface propagates even in this viscosity-dominated region of the flow.

The issue of how turbulent flow regions grow spatially when bounded by irrotational fluid is not yet fully resolved. In recent years the topic has gained new interest [7], and there are many examples of flows where turbulent/nonturbulent interfaces are of central importance, from the wakes of aircrafts to atmospheric flows, clouds, and combustion processes [8]. In all these examples the Reynolds number is very high and the flows are dominated by a mean shear. However, in most previous studies that focus on the details of turbulent/non-turbulent interface and vorticity transfer Re is low and the analysis is restricted to idealized flows, e.g. without any mean shear and rather low Reynolds number. Examples are laboratory flows of a round jet [10], direct numerical simulations of wakes and jets [1, 3], or flows with an oscillating grid [4, 5]. So, it remains questionable whether these observations also pertain to actual turbulent flows at higher Re (i.e., turbulence where the microscale and macroscale are dynamically separated) and have a mean shear.

To gain insight into the influence of shear on turbulent entrainment, a temporal plane jet with *Re* $= 2500$ is studied using Direct Numerical Simulation. For details of the code see [9]. We follow [2] but employ a larger domain of size $20b_0 \times 30b_0 \times 20b_0$ which is a large enough to be able to simulate for 200 t^*, where $t^* = b_0^2/q_0$ is the reference timescale and b_0 and q_0 are the initial width and specific volume flux, respectively. The resolution is $512 \times 768 \times 512$, for which $\Delta x/\eta$ never exceeds 2 and is less than unity for $t/t^* > 100$. Here, η is the Kolmogorov lengthscale based on the mean centerline dissipation rate ε. An analysis of spectra and correlation length confirm that the resolution is sufficient and that the domain is sufficiently large. Only data for $t/t^* > 150$ is presented and we analyse the top half of the jet.

The transition from the turbulence inside the jet to the irrotational motion outside the jet is smooth, and therefore the choice of a threshold separating the two regions is always slightly arbitrary. We opt for a threshold on the enstrophy, and consider a large number of values in the range of $\omega_0^2 \in [10^{-12}, 10^0]$ s^{-2} with a reference threshold of $\omega_r^2 = 10^{-5}$ s^{-2}. The reference threshold ω_r^2 was chosen such that the inviscid contribution to v_n is zero (see Fig. 2) which corresponds to an isosurface of enstrophy located somewhere in the viscous superlayer.

We calculate the local entrainment velocity as in [6]:

$$v_n = v_n^{\text{inv}} + v_n^{\text{vis}}, \quad v_n^{\text{inv}} = -\frac{2\omega_i \omega_j s_{ij}}{|\nabla \omega^2|}, \quad v_n^{\text{vis}} = -\frac{2\nu\omega_i \nabla^2 \omega_i}{|\nabla \omega^2|} \tag{1}$$

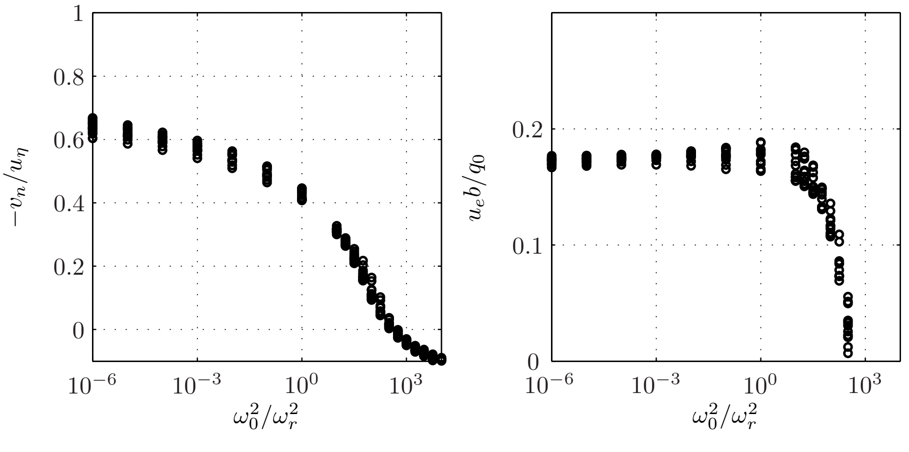

Figure 1. Entrainment velocity as a function of the threshold value ω_0^2. Left: local entrainment velocity v_n. Right: global entrainment velocity $u_e = v_n S/A$.

The local entrainment velocity v_n and the mean entrainment velocity u_e are related via $v_n S = u_e A$, where S is the surface area of the enstrophy isosurface and A the surface area projected onto the two homogeneous directions. Shown in Fig. 1 is v_n normalised by the Kolmogorov velocity u_η (left). Inside the viscous superlayer, v_n increases from 0.4 u_η to 0.6 u_η upon moving further towards the irrotational region. Also shown in Fig. 1 (right) is u_e normalized by the velocity scale q_0/b where $b(t)$ is the jet width. We note that $u_e b/q_0$ corresponds to the entrainment coefficient α upon invoking the usual entrainment assumption $u_e = \alpha q_0/b$ and observe that α has an approximately constant value of 0.17 in the viscous superlayer.

The local entrainment velocity v_n is decomposed into an viscid and inviscid contribution, v_n^{vis} and v_n^{inv} respectively (see Eq. 1). Consistent with earlier findings [6], v_n^{inv} is negligible in the viscous superlayer (Fig. 2). In the viscous superlayer $\Omega_z^2/\omega_0^2 \approx 0.03$, where Ω_z^2 is the mean vorticity in the z-direction averaged over enstrophy isosurfaces. Further decomposition of v_n^{vis} in a mean contribution $v_n^{\text{vis;av}}$ and fluctuating/ turbulent contribution $v_n^{\text{vis;turb}}$ (including cross-terms) shows that the role of the mean shear is minor, consistent with the low values of Ω_z^2/ω_0^2.

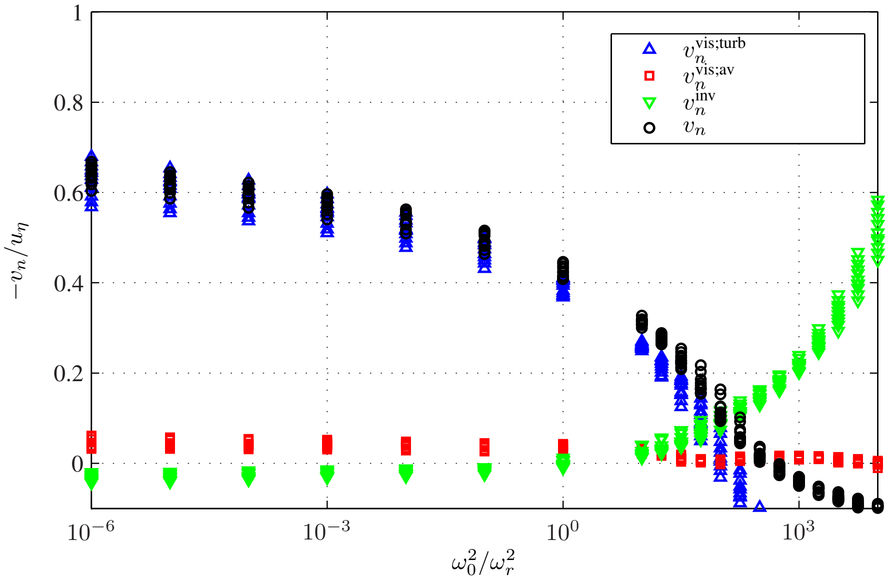

Figure 2. The local entrainment velocity v_n decomposed into an inviscid and viscid contribution, with the latter further decomposed into a mean and turbulent contribution.

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