External and Internal interfacial turbulent shear layers

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Abstract Simulation, PIV data, and local models show characteristics and conditional statistics of turbulence either side and within interfacial layers [*I*] depending on the mean profile and the presence of resistive/porous walls.
Key words; turbulence, interface structure, conditional statistics, numerical models

We consider well-developed inhomogeneous horizontal turbulent shear flows in the x direction lying beneath very thin outside interfacial shear layers [I_O] located at $z = z_I$ that separate the region [S] with strong turbulence from an outer region [O] region of weak turbulence and low shear ([2,6,9,13]). There are also gradients of mean and fluctuating concentration C in these regions and within the layer. Where the [S] region is a turbulent boundary layer above a rigid, impervious surface at z=0 or a porous rigid surface lying below z=0, internal interfacial shear layers [I_S] form near z=0, and in some cases also within [S].

In the shear region [S] below the interface, the mean velocity is $\langle u_1 \rangle$ with significant mean shear $\Omega = d\langle u_1 \rangle/dz \sim \Delta U_L/L$ below the interface, which is comparable to the large scale strain in the turbulence, $\Sigma = u'/L$, where ΔU_L is the characteristic change of the mean velocity across the scale L of the shear layer and u' is the *rms* turbulence. Note that $\Delta U_L \sim u' \sim (\tau_S)^{(1/2)}$, where τ_S is the Reynolds stress.

In the outer region [O] above [I_O] where $z = z_I + \tilde{z}$, there are two sub-regions, [O_1] lying between the mean and fluctuating positions of the interface, ie $\tilde{z} < z_I'$, for interfaces with large fluctuations. For turbulent boundary layers (see below) viscous rotational eddies detrain from [I_O] leading to significant local gradients of the conditional mean velocity, $d\langle \tilde{U} \rangle/d\tilde{z} > 0$, but eddy distortion leads to $\tau_0 < 0$. Further from the interface in [O_2] where $\tilde{z} > z_I'$, the velocity fluctuations are irrotational. For these shear flows, scalar fluctuations and fluxes are also significant in [O_1].

Within the interface, defined where the normal gradients of fluctuating vorticity are maximum ([1]), there is a thin sub-layer (or 'super layer') of thickness $l_K \sim L\, Re^{(-3/4)}$ determined by micro-scale eddies, that lies above the macro-layer $l \sim L\, Re^{(-1/2)}$ determined by large scale inertial eddies and viscous stresses ([5,6]). The mean shear below the interface, the blocking effect by the interface on turbulent eddies in [S] and the local high gradients of turbulence across the interface produce a mean jump in the tangential velocity, with mean value $\langle \Delta U_I \rangle$, which is of order u'. The inflection points $\tilde{z}_i$ of the conditional mean velocity profile in the layer $\tilde{U}(\tilde{z})$, occur where $d^2 \tilde{U}(\tilde{z})/d\tilde{z}^2 = 0$. In type JW, jets or wakes flows, $\tilde{z}_I$ lies in the super-layer. But in type BL with a turbulent boundary layer in [S], $\tilde{z}_I$ lies below the layer ($\tilde{z}_I \sim -l$). In type JW, this leads to smaller scale Kelvin Helmholtz oscillations and small scale 'nibbling' turbulence in the layer, but larger 'engulfing' amplitude fluctuations of the interface in the latter, as defined by z_I'/L. A net outward 'boundary entrainment velocity' has mean $\bar{E}_b = \langle dz_I/dt \rangle$ and fluctuating values δE_b, both of which are of the order of u'. For the particular case of jet/plume-like shear regions the mean horizontal velocity $\langle u_1 \rangle$ in the outer region [O] is small compared with $\langle u_1 \rangle$ in [S] .The outward entrainment of the interface induces a mean normal 'inwards entrainment velocity' $\langle E_v \rangle = \langle u_3 \rangle$ in the outer region [O] near [I_O]. Note that $\langle E_v \rangle$ is less than $\bar{E}_b$, and is of order u'.

In the turbulent shear layer [S] below the interface ($\tilde{z} < 0$) the mean shear stress τ_S and mean scalar flux F_C are related to the mean and fluctuating entrainment velocity $\bar{E}_b$, δE_b and the magnitudes of the jump of the conditional mean and fluctuating jump velocity, $\langle \Delta U_I \rangle$, δU_I, and for scalars $\langle \Delta C_I \rangle$, δC_I. By integrating the conditional mean momentum/scalar transport equations in the moving frame of the interface, including the correlation between the fluctuating quantities, $\langle \Delta U_I \rangle = (\tau_S - \tau_o)/\{\bar{E}_b(1 + \beta_U)\}$, where $\beta_U = \langle \delta E_b .\, \delta U_I \rangle / \{\langle \Delta U_I \rangle\, \bar{E}_b\}$. Note that for the nibbling interfaces of type JW, $\beta_U, \beta_C \ll 1$, but for the engulfing interfaces of type BL $\beta_U, \beta_C \sim 1$. This explains why in type JW, across region [S], the scalar gradient and fluctuations are relatively much weaker than in type BL. ([13])

Internal interface layers within the shear region (I_S)

Near the wall in BL at high Reynolds numbers a sharp internal interface is formed at $z = l_v \sim$ 10-15 ν/u^*, where the gradient of vorticity squared is maximum and exceeds a threshold of order $(u^*/l_v)^2$. Below this interface, i.e. $z < l_v$, the flow is a quasi-laminar with velocity fluctuations driven at the interface. Above the interface, where $z > l_v$, there is a meso-buffer layer $l_v < z < l_\mu \sim 3\, l_v \sim 30\, \nu/u^*$. The energy containing eddies are inviscid (but viscous processes maintain the local flow in equilibrium) –this is the log or surface layer, which is confined to the lower part of the turbulent boundary layer, ie $l_\mu < z << h$. In addition

(i) the blocking at the interface decorrelates the normal velocity fluctuations either side of interface at points z_1, z_2, where $z_1 < l_v$, and $z_2 > l_v$,

(ii) normal eddies in the m-b and log layers are determined by the distance from the interface so that for $z > l_\mu$, the blocking of the normal component of eddies is described by an inviscid model for the cross correlation at two points $z_1 < z_2$ i.e. $l_\mu < z << L$, $\langle w(z_1)w(z_2)\rangle / \langle w(z_1)^2\rangle \sim (z_1 - l_v)/(z_2 - l_v)$.

But note this blocking does not operate for extreme sweeps/down bursts – important for determining shear stress at the wall ([11]). This structure also provides local scaling for the variances of u, w, ([12, 4, 8]):

For $z > l_\mu$, $\langle u^2\rangle(z) \sim u^{*2}$ [ln $(L/(z - l_v)$)], while (to first order in z/L) $\langle w^2\rangle(z)$.

But at the interface where $z \sim l_v$, there is a jump in the conditional mean velocity, so that $\langle \Delta U_I\rangle \sim u^*$. As the length scale of the normal components decreases $L_x^w \sim z - l_v$, the conditional profile of the dissipation increases towards the interface $\varepsilon^{\sim} \sim (u^*)^3 / L_x^w$. This is consistent with the mean profile having a similar profile i.e. $\varepsilon \sim (u^*)^3/(z - l_v)$, for $z > l_\mu$.

(iii) Since the eddies are blocked by internal layer the mean velocity profile in the log layer, in fixed coordinates, is displaced by the height of the layer, i.e. $U(z) \sim (u^*/\varkappa)$ ln $[(z - l_v)/ l_v]$. ([3])

Other aspects of internal interface layers

(i) In turbulent boundary layers it is observed that one or more continuous internal interfaces are generated between the surface layer and the external interface, typically extending over streamwise distances of order h to $3h$, with some similarities with (I_O) and (I_S). (ii) If the bottom surface is an interface with a porous layer (z <0). This leads to another dynamic interface at z =0. (iii) The DNS results show how impinging eddies are stretched at the surface layer internal interface. If polymers are introduced, they reduce the shear in the internal interface, reduce the instabilities in the layer and significantly reduce the mean shear stress at the wall stress ([8]). (iv) The outer interfacial layers with thickness l (and probably also Internal layers) contain microscale vortices ([9]). It is also expected from studies of anomalous microscale vortices in thin layers in homogeneous turbulence, at very high Reynolds number (R_λ >~1000) ([5]). Some peak velocities on the scale are of order of the *rms* velocity u'. This would lead to very high velocities of micro particles in these layers. (v) These basic studies lead to modifications of unsteady numerical models to capture explicitly the thin interface layers and the adjacent high gradients of turbulence (by analogy with modelling flows across shock waves). A k-ε model with additional small-scale energy and dissipation near the interfaces defined at each step by smallest scale high energy eigen modes. (Intermediate organised eddy simulation). This has been applied in ([10]) to model the effects of external disturbances on turbulent boundary layers and wakes of transonic aerofoils. Another approach is to use a high-resolution eddy viscosity computation which has a time delayed negative component near the interface ([7]). This has been applied to horizontal stably stratified turbulent flows.

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