Dimensionality influence on passive scalar transport

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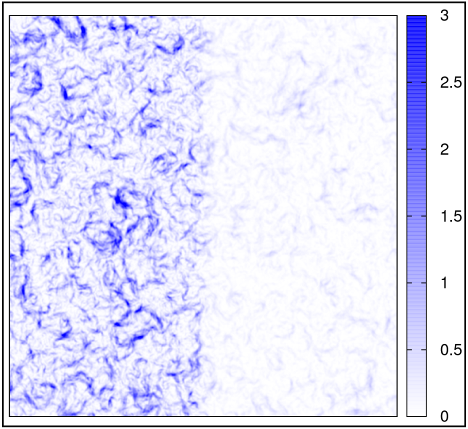
Passive scalar

Basic phenomenology

- A passive scalar is a contaminant present in so low concentration that it has no dynamical effect on the fluid motion.
- Turbulence transports the scalar by making particles follow chaotic trajectories and disperses the scalar concentration if exists scalar concentration gradient.
- Fluctuations reach the smaller scales.

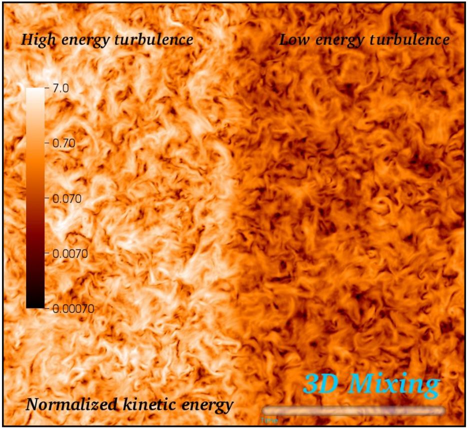
Turbulent shearless mixing

2D mixing - energy ratio $E_1/E_2 = 6.6$, equivalent $Re_\lambda = 60$



Turbulent shearless mixing

3D mixing - energy ratio $E_1/E_2 = 6.6$, $Re_\lambda = 150$



Main features of mixing layers

Shearless mixing layers shows the following properties:

- no gradient of mean velocity, thus no kinetic energy production
- the mixing is generated by the inhomogeneity in the turbulent kinetic energy and integral scale
- the mixing layer becomes very intermittent at both large and small scales
- the presence of a gradient of energy is a sufficient condition for the onset of intermittency [Tordella and Iovieno (2006), J. Fluid Mech.; Tordella et al. (2008), Phys. Rev.]
- 2D and 3D mixings: different asymptotic layer thickness growth exponent

Passive scalar transport

We solve the passive scalar advection-diffusion equation

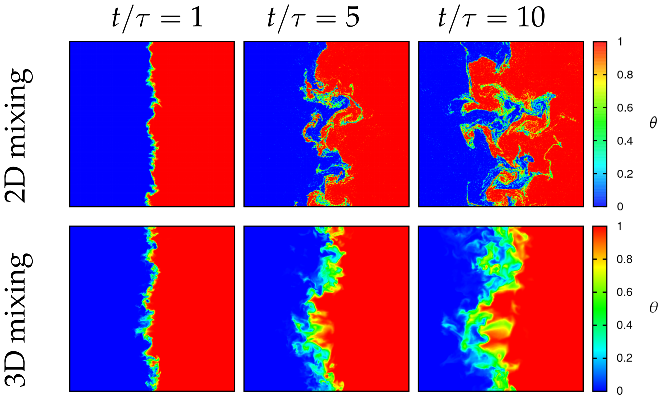
$$\frac{\partial \vartheta}{\partial t} + u_j \frac{\partial \vartheta}{\partial x_j} = \frac{(-1)^{n+1}}{Re\,Sc} \nabla^{2n} \vartheta$$

for the shearless mixing configuration.

DNS simulations have been performed at $Re_\lambda = 150$ in 3D turbulence ($600^2 \times 1200$ grid points, $n = 1$) and $Re_\lambda = 60$ in 2D turbulence (1024^2 grid points, $n = 2$).
Schmidt number $Sc = 1$

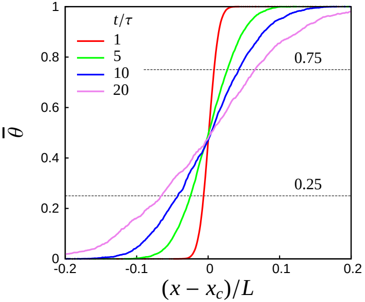
Visualizations of the mixing layer

passive scalar concentration

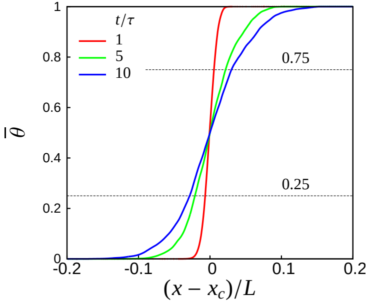


Mean Scalar Diffusion

2D Mixing



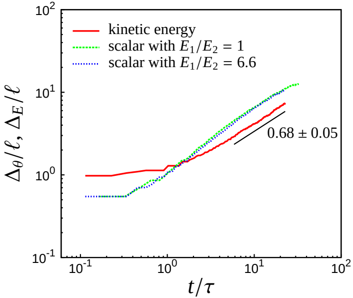
3D Mixing



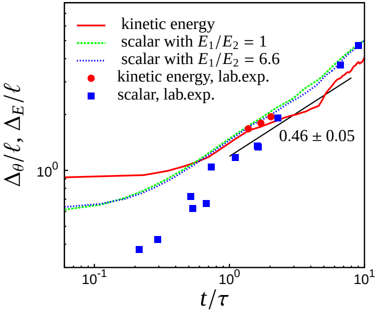
Energy ratio $E_1/E_2 = 6.6$

Scalar mixing layer thickness

2D Mixing



3D Mixing

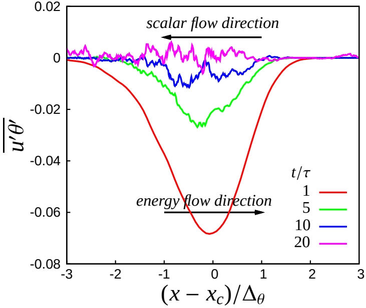


Scalar layer thickness: $\Delta_\vartheta = x_{(\vartheta=0.75)} - x_{(\vartheta=0.25)}$

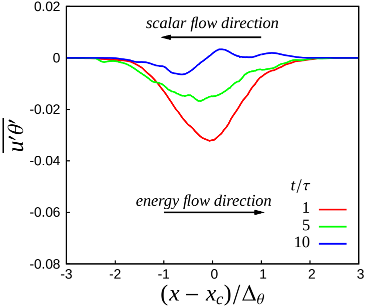
3D mixing: $\Delta_\vartheta \sim t^{0.45}$, 2D mixing: $\Delta_\vartheta \sim t^{0.68}$

Scalar flux

2D Mixing



3D Mixing

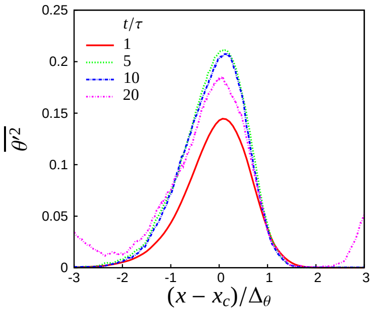


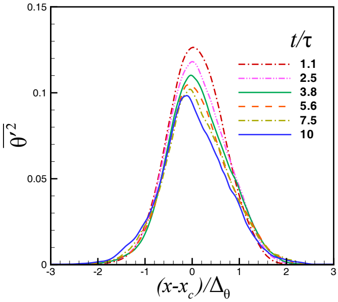
$$\overline{u'\vartheta'} \sim 1/\Delta_\vartheta(t)$$

Scalar variance

2D Mixing

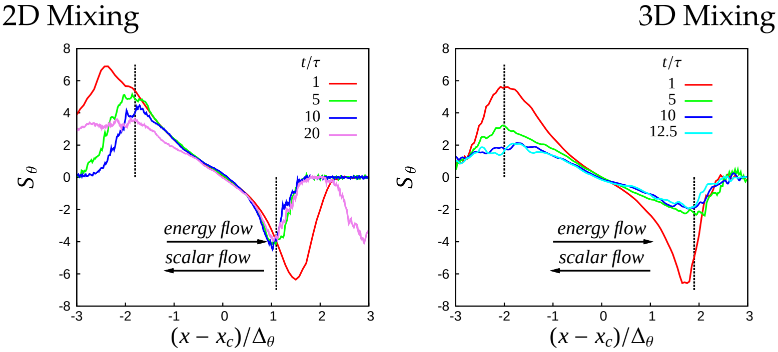
3D Mixing





Self-similar distribution, peak shifted toward the high kinetic energy region

Scalar skewness

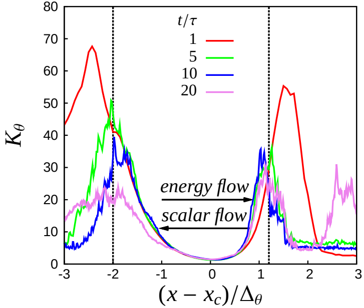


Strong non-gaussian statistic at the mixing layer border

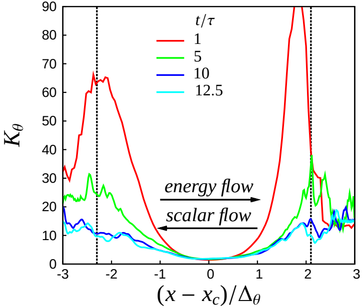
2D: intermittency penetrates more in the direction opposite to the energy gradient.

Scalar kurtosis

2D Mixing



3D Mixing



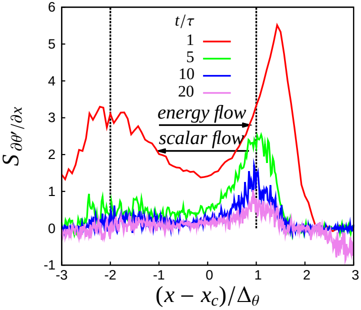
2D: higher asymmetry of the peaks.

Intermittency gradually reduces as the mixing procedes

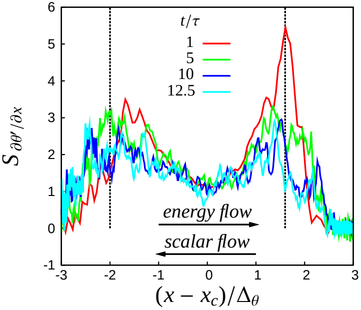
Small scale intermittency

Scalar derivative skewness

2D Mixing



3D Mixing



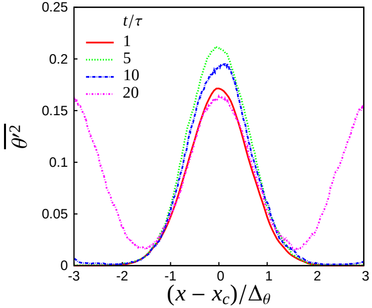
2D: higher asymmetry of the peaks.

Intermittency decay faster in 2D

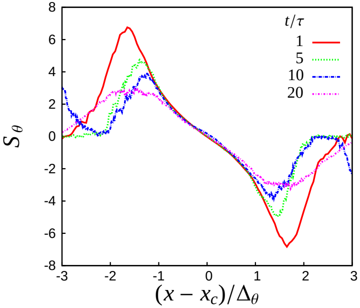
No energy gradient

2D mixing

Scalar variance



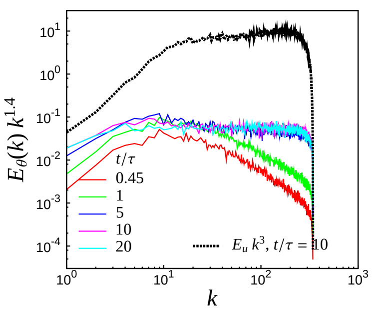
Scalar skewness



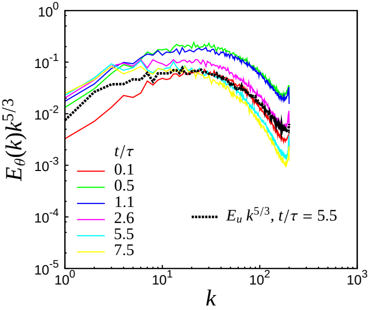
No energy gradient $\Rightarrow$ no asymmetry

Spectra in the mixing layer

2D Mixing



3D Mixing



Compensated scalar and velocity one-dimensional spectra in the same position

Conclusions

2D/3D Passive scalar diffusion in the mixin layer:

- 2D simulation : $(\Delta_\vartheta \sim \Delta_E \sim t^{0.68})$.
- 3D simulation : $(\Delta_\vartheta \sim \Delta_E \sim t^{0.46})$.
- Self-similar profiles of first and second order moments. The scalar flow is about two times larger in 2D than in 3D. The scalar variance in the center of the mixing layer is 50% higher in 2D case.
- Large intermittency and non-gaussian behaviour on both sides of the mixing, even where the scalar flux is small.
- Larger asymmetry in moment distributions in 2D mixing.

Conclusions

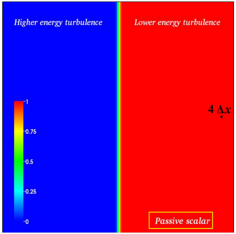
- intermittency involves also the small scale
- 3D inertial range spectra exponent of velocity and passive scalar $\sim -5/3$
- 2D inertial range spectra exponent of velocity ~ -3 and passive scalar ~ -1.4

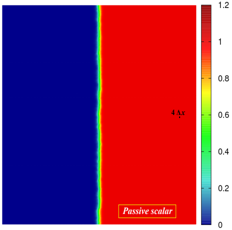
Mixing

passive scalar

3D Mixing
($600^2 \times 1200$ grid)

2D Mixing
(1024^2 grid)





Run 3D Movie

Run 2D Movie