Shearless turbulent mixing

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Abstract. – *This work focuses on the numerical simulation of the intermediate asymptotics of turbulent diffusion in absence of turbulent kinetic energy production. Shearless turbulent mixings, which occur between two homogeneous and isotropic turbulent flows with different properties, are the simplest inhomogeneous turbulent flow and allow to enlighten the mechanisms of self-interaction of turbulent scales without being concealed by energy production due to the presence of a mean shear. The present results complement data available in literature and show the scaling of the intermittency with the governing parameters, the ratios of energy and scale through the mixing and the Reynolds number.*

Introduction

The interaction of turbulence fields with different energy and macroscales is very frequent both in nature and in engineering contexts. Among them, shearless mixings are possibly some of the simplest due to the absence of mean shear. For the same reason, they are of very fundamental interest because they allow to enlighten the mechanisms of turbulence self-interaction without being concealed by turbulence production and mean shear instabilities. Only few studies of shearless mixing layer have been published up to now in the literature to understand the interaction of two dominant energy-containing scales, see the experiments by Gilbert [1] and Veeravalli and Warhaft [2] and the numerical simulations, both direct and large-eddy simulations, by Briggs *et al.* [3], Knaepen *at al.* [4] and Tordella and Iovieno [5]. Experimentally, turbulences with different intensities were generated in a wind channel by two different sized grids but with the same aspect ratio in order to maintain the same mean velocity. As a consequence, the gradient of turbulent kinetic energy and the gradient of integral scales are not independent because higher energies are always associated to larger scales in grid turbulence. Even if numerical experiments do not have such a limit, most of them ([3], [4]) mainly repeated the laboratory experiment with a single energy ratio between the two flows. An attempt to investigate the dependence of of the intermittency from the main governing parameters had been performed (Tordella and Iovieno [5]) using direct numerical simulations to investigate the effect of a scale gradient with a fixed energy ratio, while mainly large-eddy simulations where used to investigated the effect of an energy gradient in the absence of an integral scale gradient. A similarity analysis, which is in fair agreement with the previous experiments, has been presented in [6]. It is based on the energy equation, which contains information concerning the third order moments of the velocity fluctuations, and uses two simplifying hypotheses: first, that the rate of decay of the turbulence fields being mixed are almost equal, second, that the pressure-velocity correlation is almost proportional to the convective transport associated to the fluctuations.

In this work within HPC-Europa program, we seek to verify the intermittency scaling for low to moderate energy ratios and compare results at two Reynolds numbers.

Method

Navier-Stokes equations are numerically solved with a fully dealiased Fourier-Galerkin pseudospectral method (for a full description of the code and of the numerical methods implemented see Iovieno *et al.* [7]). The computational domain is a parallelepiped with dimensions $4\pi \times 2\pi \times 2\pi$, with the larger dimension in the mixing direction, and the boundary conditions are periodic in all directions. Initial conditions are generated by matching two velocity fields coming from simulations of homogeneous turbulence simulations by means of a hyperbolic tangent which generates an initial smooth thin layer (about 1/40 of the domain size) between the two flows. With these initial conditions it is possible to generate a real mixing layer in a much shorter time than with initial conditions generated by a random superposition of Fourier modes with prescribed amplitude and spectrum. Two Reynolds numbers have been tested: $Re_\lambda = 44$, roughly corresponding to that of Veeravalli and Warhaft experiments, and $Re_\lambda = 67$. Consequently, two resolution have been used: a lower one (256×128^2) for the lower Reynolds number simulations and a higher resolution of (384×192^2) for the higher Reynolds number simulations. Note that this is the resolution after dealiasing, actual resolution in the wavenumber space with 3/2-dealiasing rule is higher, i.e. 576×288^2 and 384×192^2 respectively.

Results

Under the hypothesis that the two flows which are going to mix are homogeneous and isotropic turbulent decaying flows at high Reynolds numbers, each field is defined by two parameters in Kolmogorov's theory: its kinetic energy and integral scale. Thus, apart from the Reynolds number, by standard dimensional analysis only two parameters characterize the mixing: the ratio $\mathcal{E}$ of their energy and the ratio $\mathcal{L}$ of their integral scales. If the Reynolds number is high enough, the two turbulences outside the mixing decay algebraically with the same exponents, so the initial ratios of energy and scales remain constants through the whole mixing process.

Two sets of numerical experiments have been performed: a first one to determine the scaling law of intermittency as function of the energy ratio, a second one to investigate the influence of an opposite gradient of scales on the intermittency. In both

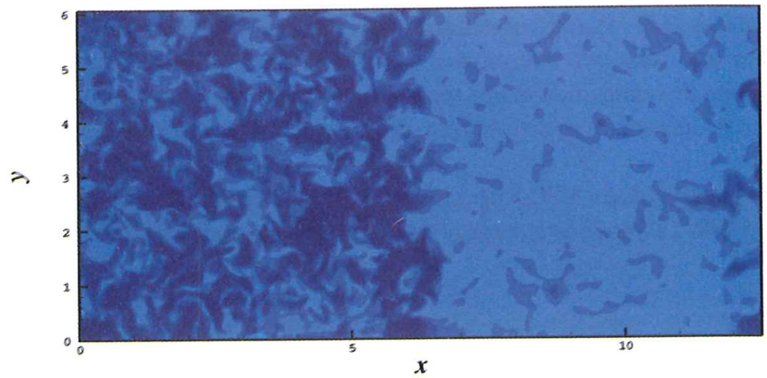

FIGURE 1. – *Kinetic energy contours for the mixing with $\mathcal{E} = 12$ at dimensionless time $tE_1(0)^{1/2}/\ell_1(0) = 3.2$. High energy region is on the left, low energy region on the right.*

cases the two resolutions allowed to check the Reynolds number effect. An example of flow realization is given in figure 1. While most of results I present concerns single-point velocity statistics, also two-point correlations and velocity derivative moments were also evaluated. All processed data have been make dimesionless using the instantaneous mixing thickness $\Delta(t)$ and the high energy region energy $E_1(t)$ and self-similar disdistribution moments have been always obtained for all simulations.

The main parameter which characterize the mixing is the distribution of the skewness $\overline{u^3}/\overline{u^2}^{3/2}$ of the velocity component along the direction normal to the

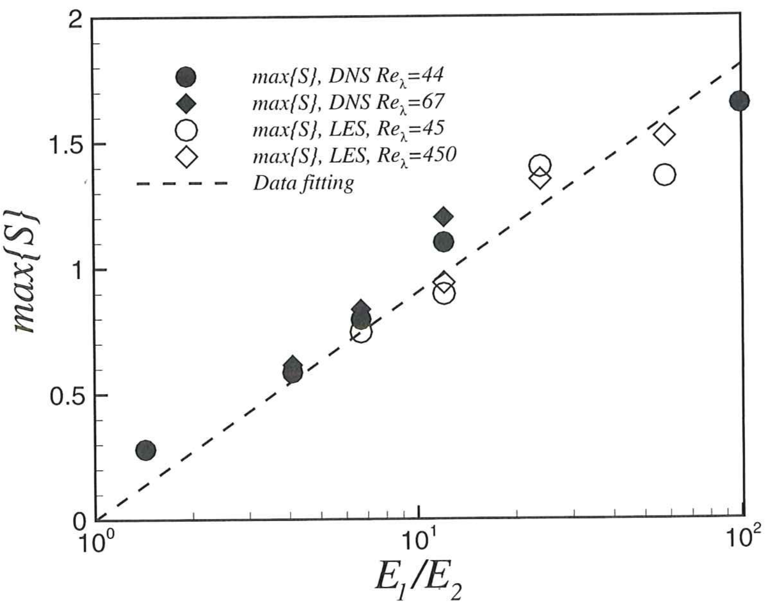

FIGURE 2. – *Maximum of velocity skewness as function of the initial energy ratio for simulations without gradient of scale. Large-eddy simulation data from [5] are also shown.*

mixing. It is a normalized energy flux and gives information about the departure from an almost gaussian statistics of homogeneous turbulence, where it is null. In particular it reaches its maximum in the low energy side of the mixing layer. When the maximum values and its position are considered as a measure of intermittency, it has been noted that, at least when the ratio of energy between the two homogeneous fields that generate the mixing is kept between 1 and 100, it scales almost linearly with the logarithm of the energy ratio, almost in good agreement with similarity equations (Tordella and Iovieno [6]) for one-point correlations. In figures (2) and (3) the position and the value of the maximum of skewness is shown as function of the initial energy ratio $\mathcal{E} = E_1(0)/E_2(0)$ when the turbulent flows outside the mixing have the same integral scale. The scaling derived from the data fitting has been also shown. Values are always lower than the corresponding self-similar solution, in particular for high energy ratio, but this could be due to the finite Reynolds number of simulations in contrast with the hypothesis of local equilibrium and high Reynolds scaling of energy decay. This is more evident in the higher part of the range of parameters investigated, because there one of the two turbulent fields had too few energy to allow a proper power law decay, so that the actual instaneous energy gradient tends to slowly decrease during the mixing and is lower then the initial one, while on the contrary for lower energy ratios the two decay exponents are very close even if higher than the infinite Reynolds number limit. This is probably a limit of the numerical simulations.

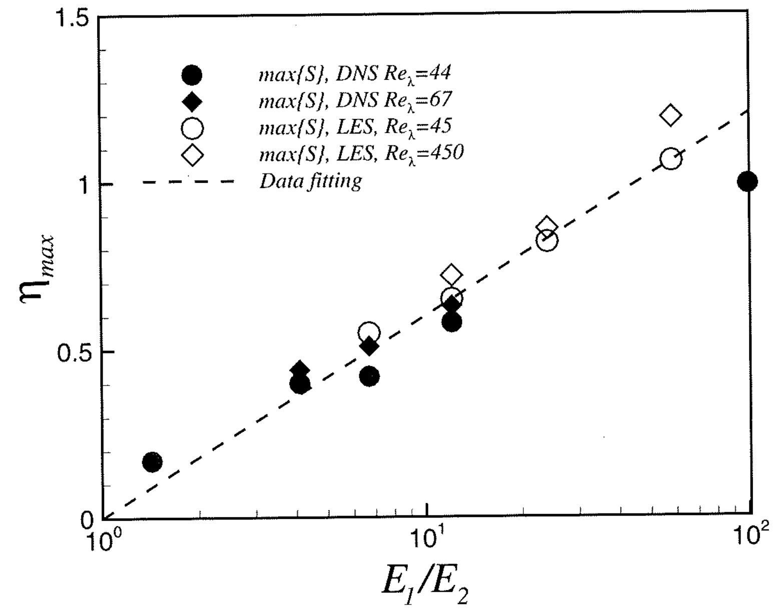

FIGURE 3. – *Normalized position $\eta = x/\Delta(t)$ of the maximum of velocity skewness as function of the initial energy ratio for simulations without gradient of scale. Large-eddy simulation data from [5] are also shown.*

The second set of simulations confirmed that a gradient of scales opposite to the gradient of energy always has the effect of reducing intermittency and intermittent penetration, but this effect saturates quite early, so that normalized scale gradients less higher than one have almost no influence. The computation of two-point correlations enlighted that a local equilibrium hypothesis is not valid when a scale gradient is present and gave information useful to model the two-point correlation equations. Comparison between simulations with a different Reynolds number have confirmed the importance of large scale inhomogeneities and of the minor role of small scales in these mixings. In fact, differences in velocity derivative skewness, which depends on the fine structure of turbulence, do not reproduce significant differences in the global character of intermittent penetration, thus confirming that the global character of the mixing layer is mainly determined by the large scale inhomogeneity of turbulence. This could be also important for physical and engineering applications, because it means that shear-free mixing of turbulence can be fairly reproduced by large-eddy simulations.

Results of this work have been accepted to the next Efmc-6 conference [8].

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