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PASSIVE SCALAR PDF IN INHOMOGENEOUS AND ANISOTROPIC TURBULENCE: EXPERIMENTS AND STOCHASTIC MODELLING

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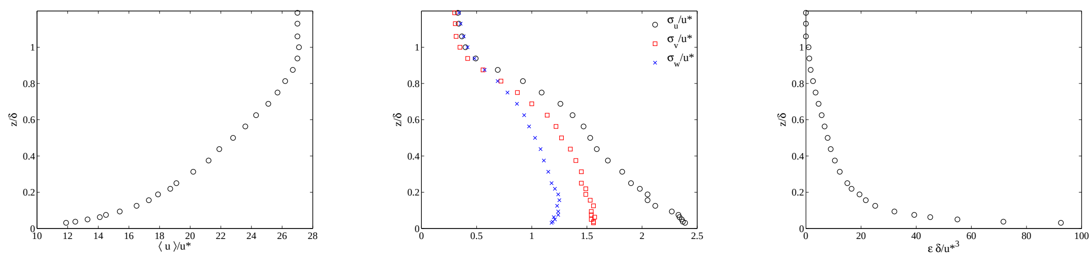
Abstract We investigate the concentration fluctuations in plumes of passive scalars emitted from point sources in a neutral boundary layer by means of experiments and numerical simulations, performed through a Lagrangian stochastic micromixing model. Different configurations are considered in order to study the effects of the source characteristics - size, height, source outlet conditions - on the concentration PDFs. Varying the source conditions directly affects the main mechanisms that are responsible for the scalar dispersion, namely the size of the eddies governing the plume dynamics. We show that the model is able to reproduce these mechanisms, but it is extremely sensitive to the numerical setting of the source conditions.

EXPERIMENTS

We experimentally investigate the dispersion of a passive scalar from a point source in a neutral boundary layer. The dynamics of the turbulent flow is measured by means of Hot Wire Anemometry. The adimensional vertical profiles of the statistically steady state turbulent field - longitudinal mean velocity $\langle u \rangle$, r.m.s. of the velocity components (σ_u, σ_v, σ_w), turbulent kinetic energy dissipation rate ε - are reported in Fig. 1. Ethane is used as passive scalar and its concentration is measured by means of a Flame Ionization Detector (FID). Experiments provide the concentration PDFs at increasing distance from the source location. The influence of the source characteristics - size and height - on the concentration distribution and the effects of the source outlet velocity are evaluated. Different experimental configurations are performed: two source diameters, 3 and 6 mm, two source positions z_s/δ, 0.19 and 0.06, two conditions of release velocity, isokinetic and ipokinetic.



(a) (b) (c)

Figure 1. Non dimensional vertical profiles of a) mean longitudinal velocity; b) r.m.s. of the velocity components; c) turbulent kinetic energy dissipation rate (δ is the boundary layer depth and u^* the friction velocity).

MODEL

Spatial evolution of passive scalar PDFs is computed by a Lagrangian Stochastic (LS) micromixing model. The model aims at simulating the combined effect of turbulent dispersion and molecular diffusivity on high order moments of the concentration PDF. The particle position $\mathbf{X}$ and velocity $\mathbf{U}$ are governed by LS trajectory model; the temporal evolution of the particle concentration ϕ is described by the Interaction by Exchange with the Conditional Mean (IECM) model. The governing equations are

$$dU'_i = a_i(\mathbf{X}, \mathbf{U}', t)dt + b_{ij}(\mathbf{X}, \mathbf{U}', t)d\xi_j, \tag{1}$$

$$dX_i = (\langle u_i \rangle + U'_i)dt, \tag{2}$$

$$\frac{d\phi}{dt} = -\frac{\phi - \langle \phi | \mathbf{X}, \mathbf{U} \rangle}{\tau_m}, \tag{3}$$

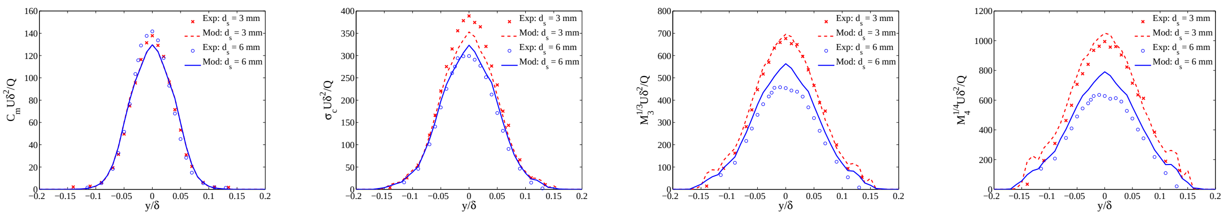
where the deterministic acceleration a_i and the stochastic diffusive term b_{ij} are determined in order to satisfy the well-mixed conditions [3]. Eq. (3) models the passive scalar diffusive transfer between different fluid particles: $\langle\phi|\mathbf{X},\mathbf{U}\rangle$ is the mean scalar concentration conditioned on the local position and velocity, the scalar micromixing time τ_m represents the temporal scale of molecular diffusion and it is parametrized following the formulation of Cassiani et al. [1].
The concentration $\langle\phi|\mathbf{X},\mathbf{U}\rangle$ and the micromixing time are pre-computed on a homogeneous structured grid by simulating the trajectories of a continuous release of N particles from the source (Eqs. (1) and (2)). The concentration fluctuations are calculated following the approach of Cassiani et al. [2]: at the first timestep, for each space element, N particles are released with a concentration ϕ initialized to zero and the evolution of the concentration is governed by Eq. (3). The global number of particles is conserved constant by imposing suitable boundary conditions. In order to take into account the source, the near-source particles are marked by a scalar concentration ϕ_{src} defined by a two-dimensional isotropic Gaussian distribution in the yz-plane centred on the source location (y_s, z_s) and with a variance σ_0^2 depending on the source diameter d_s:

$$\phi_{src} = \frac{Q}{2\pi\sigma_0^2\langle u\rangle}\exp\left(-\frac{r^2}{2\sigma_0^2}\right), \tag{4}$$

where r is the distance from the source location and Q is the mass rate. Cassiani et al. [2] observe that the increase of the number of velocity classes used to estimate $\langle\phi|\mathbf{X},\mathbf{U}\rangle$ produces a small improvement in the solution accuracy with high computational costs; therefore the simulations are performed with $3\times3\times3$ velocity classes.

RESULTS

The numerical profiles of the first four concentration moments are compared with the experimental results. The agreement between the numerical results and the experiments is satisfactory both in the near and far field. A displacement between the experimental and numerical vertical profiles is observed close to the source, probably due to some wake effects. Fig. 2 represents the lateral profiles of the first four adimensional concentration moments at the source height and at a distance from the source location x/δ equal to 0.625. It is worth noting that the mean concentration is independent of the source diameter (Fig. 2(a)), whereas the concentration fluctuations increase with the decrease of the source size (Figs. 2(b), 2(c), 2(d)): the model is able to simulate this effect for the 2^{nd}, 3^{rd} and 4^{th} order moments. We also investigate the



(a) $\frac{C_m U\delta^2}{Q}$ vs $\frac{y}{\delta}$ (b) $\frac{\sigma_c U\delta^2}{Q}$ vs $\frac{y}{\delta}$ (c) $\frac{M_3^{1/3} U\delta^2}{Q}$ vs $\frac{y}{\delta}$ (d) $\frac{M_4^{1/4} U\delta^2}{Q}$ vs $\frac{y}{\delta}$

Figure 2. Concentration statistics vs y/δ evaluated at the source height and $x/\delta = 0.625$.

influence of the source height showing that the micromixing model reproduces as well configurations of large shear, that are usually critical configurations for most of the analytical models. The effect of varying release velocity at the source is also studied. Experimental data show that the concentration field is extremely sensitive to the source conditions, until a distance of almost 100 times the source diameter. These effects can be modelled suitably initializing the stochastic diffusive term b_{ij} in Eq. (1).

References

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