POLLUTANT CONCENTRATION FLUCTUATIONS IN A NEUTRAL ATMOSPHERIC BOUNDARY LAYER: A NEW DETAILED DATA SET FOR THE VALIDATION OF DISPERSION MODELS

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Abstract: A new experimental dataset is presented for the validation of dispersion models, providing a detailed description of the evolution of a fluctuating pollutant plume emitted by a point source within the turbulent boundary layer. The dataset includes concentration third and fourth moments, whose computation is essential when dealing with highly skewed distributions, and the investigation on the influence of the source size on concentration statistics. A detailed description of the velocity field is also provided.

Key words: *concentration fluctuations, concentration PDF, turbulent boundary layer, dispersion models***.**

INTRODUCTION

In recent years, considerable attention has been focused on the prediction of concentration Probability Density Functions (PDFs) downwind a point source in a Turbulent Boundary Layer (TBL). This is due to the increasing interest on the risk assessment of hazardous releases of toxic or flammable substances, and on problems related to odours. When dealing with such problems, the knowledge of the concentration mean and standard deviation is not sufficient to predict peak concentrations, which requires information about higher order moments of the concentration PDF. To these purposes several modelling approaches can be adopted, such as analytical meandering models (e.g. Yee and Wilson, 2000) or micro-mixing stochastic models (e.g. Cassiani et al, 2005).
The reliability of these models has however to be tested against field or experimental data providing a detailed description of the concentration and of the velocity statistics. The motivation of our work is to provide a complete dataset describing the evolution of a fluctuating pollutant plume within the TBL. We aim to extend the popular study of Fackrell and Robins (1982b), hereafter referred to as FR, about concentration fluctuations and fluxes from point sources by including measurements of concentration skewness and kurtosis. We also further inquire into the influence of source conditions, such as the source size, on higher order concentration moments. The data set is completed by a detailed description of the velocity statistics within the TBL, with exhaustive information on both the temporal and spatial structure of the flow.

INFLUENCE OF THE SOURCE SIZE

The influence of the source size on concentration fluctuations can be outlined by assuming the framework developed by Gifford F. (1959). In his model, the spread of a plume of contaminant is led by two phenomena: a meandering movement of the instantaneous plume, causing the displacement of the mass center, and the instantaneous relative dispersion, or spreading, of the plume particles relative to the mass center position.
Assuming that these phenomena are statistically independent, since they are related to different length scales, the total plume spread σ can be calculated as the sum of a contribution due to the meandering (σ_m) and another due to the relative dispersion (σ_r): $\sigma^2 = \sigma_m^2 + \sigma_r^2$. The predominance of one of the two depends on the plume scale compared to the turbulence length scales, at a given distance downwind. In the near field, meandering is the major contribution to concentration fluctuations. From dimensional considerations, the intensity of the concentration fluctuations σ_c due to the meandering motion can be written as: $\sigma_c \sim (\sigma_v\, x/(U\, \sigma_0))^2$, where σ_v is the lateral turbulence level, U is the mean velocity and σ_0 is the initial spread due to the source size (Fackrell and Robins, 1982b). Therefore, in the near field, the smaller sources generate higher concentration fluctuations. Moving far from the source the plume begins to develop a finer scale structure also resulting in fluctuations: meandering is not the only source of fluctuations and the relative dispersion becomes more and more influent.

EXPERIMENTAL SET-UP

The experiments were performed in the atmospheric wind tunnel of the Laboratoire de Mécanique des Fluides et d'Acoustique de l'Ecole Centrale de Lyon (France): a recirculating wind tunnel with a working section 14 m long, 2.5 m high and 3.7 m wide. In the wind tunnel, a neutrally stratified boundary layer was generated by combining the effect of a row of spires at the beginning of the test section (Irwin, 1981) and floor roughness elements. This experimental set-up allowed us to reproduce a neutral boundary layer whose depth δ was approximately 0.8 m. The reference free-stream velocity U_∞ at the boundary layer height was set at 5 ms^{-1}. The Reynolds number $Re = \delta\, U_\infty/\nu \approx 2.6\cdot10^5$ is sufficiently high to ensure the adequate simulation of a fully rough turbulent flow (Jimènez, 2004).
The flow dynamics above the obstacle array were investigated by means of hot-wire anemometry, using an X-wire probe with a sampling frequency of 5000 Hz. Concentration measurements were performed with a Fast Flame Ionisation Detector (FID) by detecting a gas tracer continuously discharged with a mass flow rate M_q.

Ethane (C_2H_6) was used as tracer in the experiments. This gas is not reactive and has a density similar to air, thus the release obtained was neutrally buoyant and passive.
The source was placed at a distance from the ground $z_s/\delta = 0.19$, z_s being the source elevation, and at a distance 7.5δ from the entrance of the test section, where the boundary layer was fully developed. To investigate the effects of source size we used two source diameters: 3 mm and 6 mm. The emission was isokinetic, with an outlet velocity equal to the surrounding flow one.

THE VELOCITY FIELD

Velocity profiles were recorded starting from a distance of 6.25δ from the entrance of the test section. At this distance we assume that the development of coherent structures in the wake of the vortex generators has already reached an equilibrium condition and the dynamics of the flow field depend only on the scales imposed at the wall and on the boundary layer depth (Salizzoni et al., 2008).

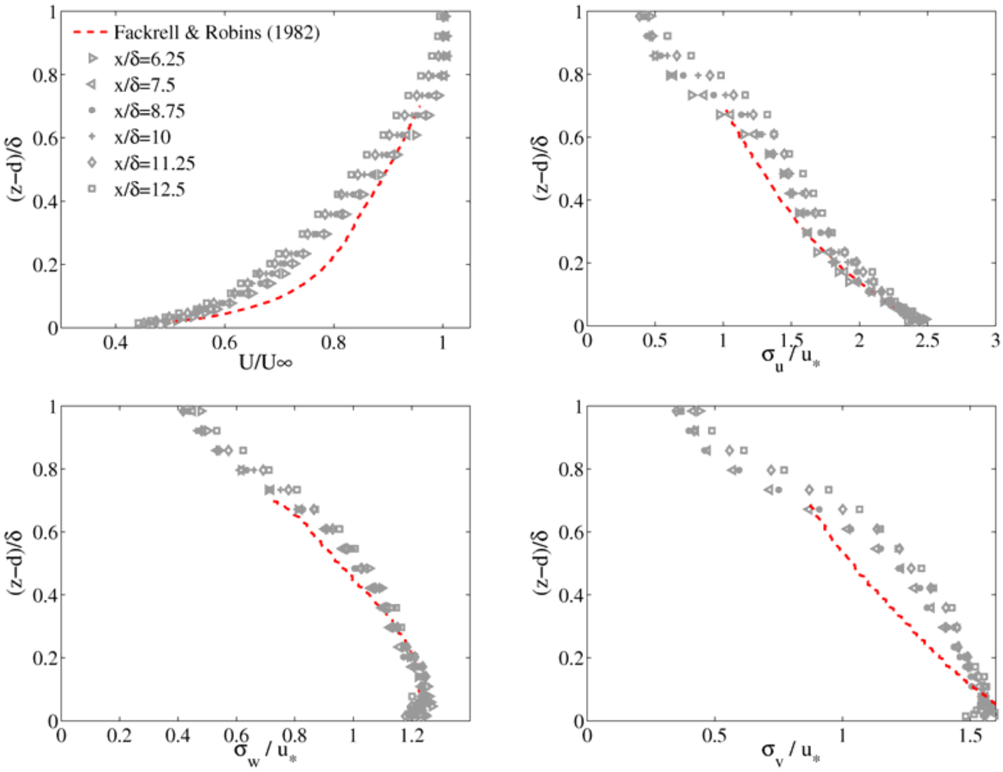


Figure 1. Normalised velocity profiles (mean U, σ_u, σ_w, σ_v) and comparison with literature data from Fackrell J. E. and Robins A. G.,1982b.

Figure 1 shows vertical profiles of the non-dimensional mean stream-wise velocity U and of the statistics σ_u, σ_w, σ_v compared to those measured by FR. Profiles show little evolution with the stream wise distances from the test section entrance. According to the similarity theory (Tennekes and Lumley, 1972), we can reasonably consider that the flow is homogeneous in the horizontal planes and fit the mean velocity profile with a logarithmic law, obtaining estimates of friction velocity[1] $u_* = 0.23$ ms^{-1}, the roughness length z_0 was $1.14 \cdot 10^{-4}$ m. These yield to non dimensional values of $u_*/U_\infty=0.046$ which equal to that estimated in the FR experiment, and $z_0/\delta=1.42\ 10^{-4}$ that is smaller than the FR value by a factor of two. This difference can be the reason for the discrepancies that can be observed in the profiles of U/U_∞ (Figure 1), showing higher mean velocity gradients close to the wall in the FR experiment. Further comparison with profiles from FR shows an overall agreement for non-dimensional profiles of σ_u and σ_w and non negligible discrepancies σ_v
Spectra of the three velocity components u, v and w are shown in Figure 2, for growing distance from the ground. Spectra are normalized by u_* and plotted against the dimensionless frequency $n=fz/U$. The measured spectra show good agreement with the model proposed by Kaimal et al. (1972), based on the Kansas field measurements in neutral conditions, for the large scale and the inertial range.

[1] It is worth noting that the friction velocity u_* estimated by the Reynolds stress profile is $u_* = 0.185$ ms^{-1}.

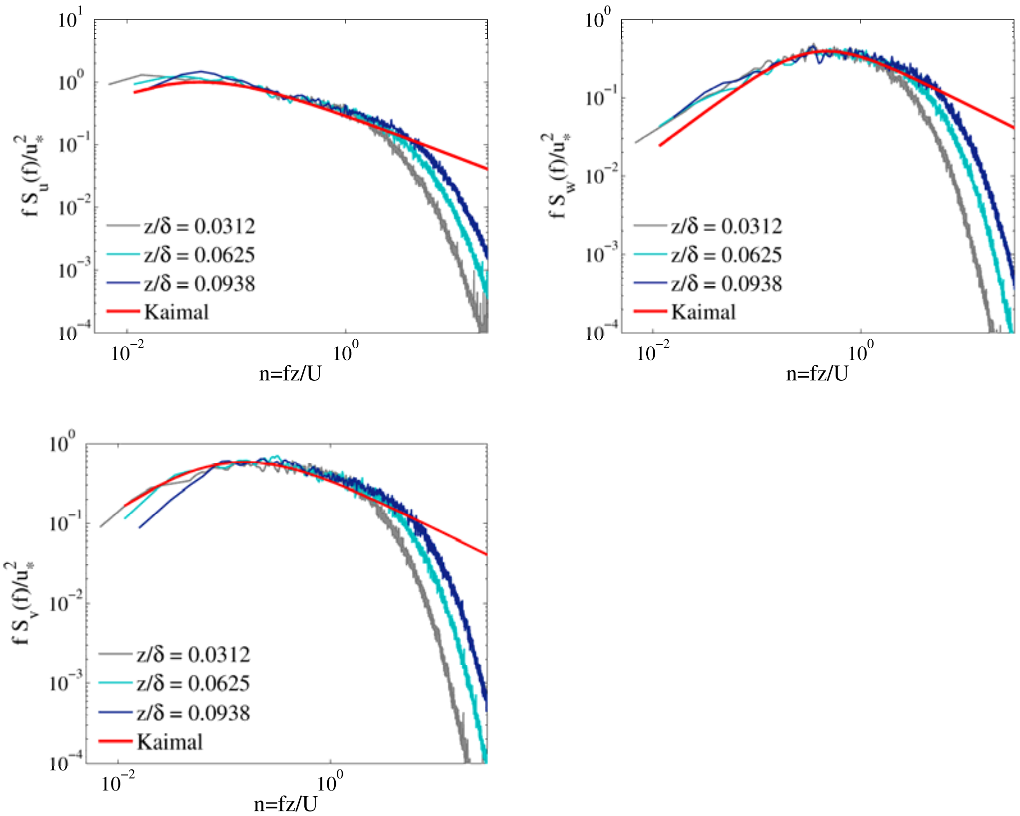


Figure 2. Velocity spectra for growing distances from the wall z/δ for the three velocity components. Comparison with model extrapolated from field data (Kaimal et al., 1972).

THE CONCENTRATION FIELD

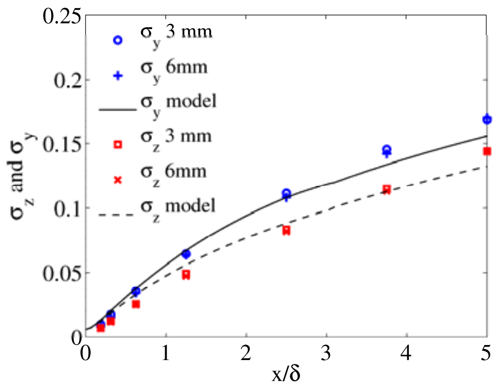


Figure 3. Vertical and lateral plume spreads from experimental data and comparison with the model (Eq. 1).

Instantaneous concentrations were recorded over 5 minutes for each measurements points. From these we could compute the first four moments of the concentration PDF. The dataset contains vertical profiles at the plume centreline and horizontal profiles at the source height for 6 stream-wise distances from the source.

As expected, the mean concentration field was not sensitive to the size of the source. The plume spreads σ_y and σ_z of the mean plume could be estimated by fitting the vertical and horizontal profiles with a bi-Gaussian curve. Their evolution down-wind the source is reported in Figure 3. The plume is spreading in the transversal direction more than in the vertical one, where is bounded by the presence of the ground. Experimental plume spreads show good agreement with analytical models relating the plume spread with the Eulerian spectrum of velocity fluctuations. In the lateral direction, σ_y is given by:

$$\sigma_y^2 = \sigma_0^2 + (\sigma_v^2/U^2)x^2 \int_0^\infty F_{Ev}(k)\left(\frac{\sin kx/2\beta}{kx/2\beta}\right)^2 dk \qquad (1)$$

where $F_{Ev}(k) = E_E(k)/\sigma_v^2$ is the normalized Eulerian spectrum. It is assumed that Eulerian $E_E(k)$ and Lagrangian $E_L(k)$ spectra are related via $E_L(f)=\beta E_E(\beta f)$. β is the ratio between Eulerian and Lagrangian scales and is a function of the distance from the source. The same relation can be written for the vertical direction, assuming that $F_{Ew}(k) = E_E(k)/\sigma_w^2$.

The influence of the source size on higher order statistics is evident in the profiles reported in non-dimensional form in Figure 4, assuming as a characteristic concentration scale $\Delta c = M_q / U_\infty \delta^2$. The plotted profiles were measured on the plume centreline (*y=0*), at a distance from the emission point equal to $x/\delta = 1.25$, i.e. at a distance of hundreds source size. Although the mean concentration are unaffected by different source diameter, this has an evident influence on the higher order concentration statistics. The plume emitted by smaller source shows higher concentration fluctuations, resulting in higher standard deviation, skweness and kurtosis.

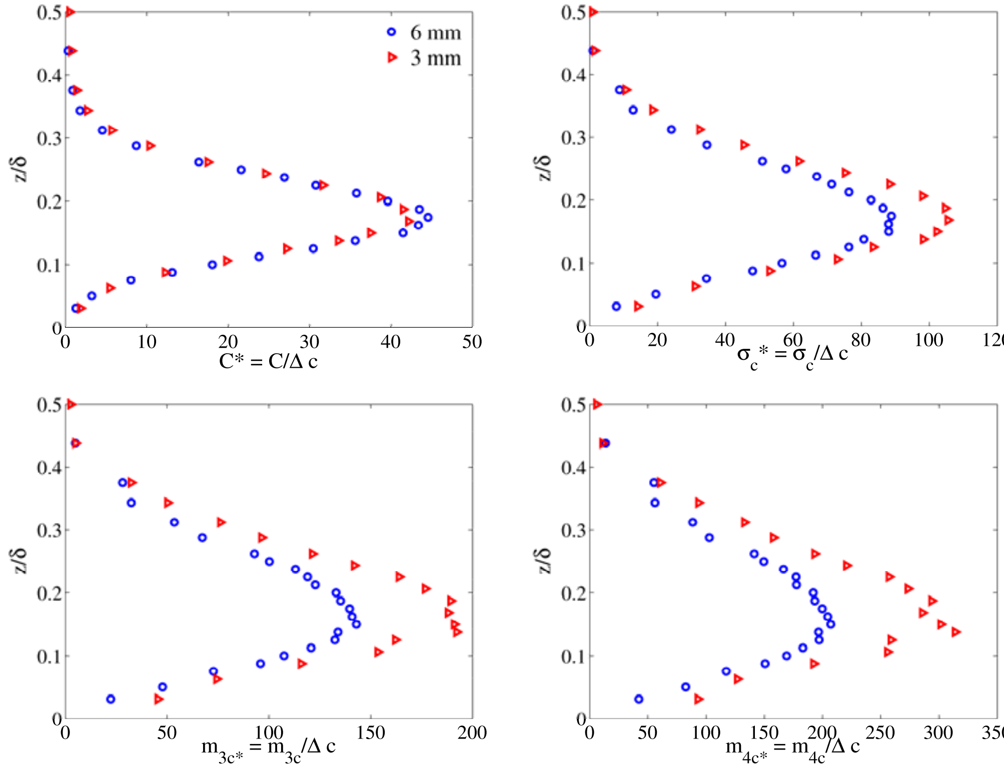
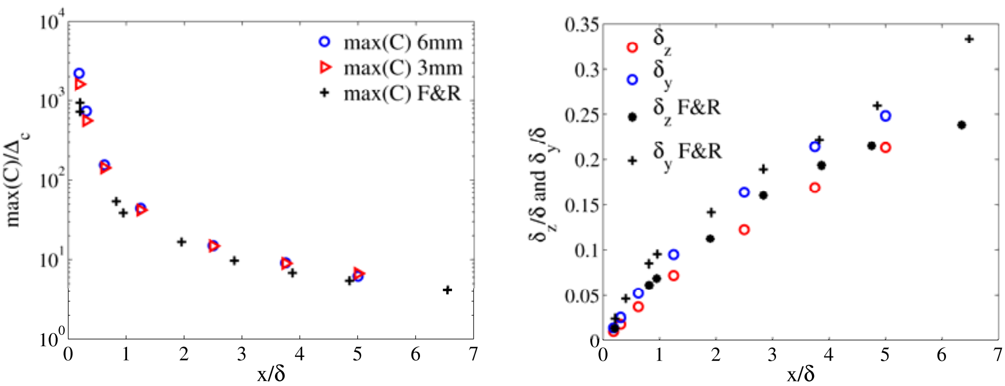


Figure 4. Vertical profiles of concentration statistics (mean, standard deviation, third and fourth moments) measured on the plume axis, at a distance $x/\delta = 1.25$ from the emission point. Comparison between two source dimensions.



(a) (b)

Figure 5. (a) Maximum concentrations and (b) vertical and lateral half-plume widths downstream the source. Comparison with Fackrell J. E. and Robins A. G. (1982b) (F&R in the legends).

Comparisons with FR results are performed focusing on the maximum non-dimensional mean concentration *max(C)*, the plume half-widths δ_y and δ_z, defined as the distance in which the maximum concentration falls to its half value, and the intensity of the concentration fluctuations at source height and plume centreline.

The variation of *max(C)* and of plume half-widths δ_y and δ_z with downstream distance are shown in Figure 5(a)-(b). Little differences are observed between the mean concentration fields of two experiments. Generally our data show lower dilution of the passive scalar, with slightly higher values of *max(C)* and slightly lower values of the plume half-widths δ_y and δ_z.

More significant differences between the two experiments can be observed on the behaviour of the intensity of concentration fluctuations at every downstream position. As Figure 6 shows, the maximum of the fluctuation intensity occurs close to the source and thereafter the fluctuations decay. The effect of source size is stronger in the near field, where the highest fluctuations result from the small size emissions, and decreases with increasing the distance from the source: at the latest station the curves converge to common far field behaviour, as it is logically attended. Non-negligible differences emerge in comparison to Fackrell. and Robins (1982b), whose plume exhibits all along higher fluctuations. These discrepancies are likely to be attributed to the differences observed in the velocity field.

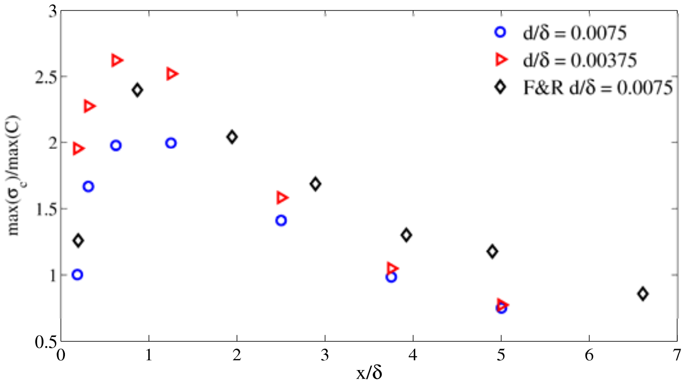


Figure 6. Development of the intensity of concentration fluctuations $\max(\sigma_c)/\max(C)$, at every downstream position. Comparison with Fackrell J. E. and Robins A. G. (1982b).

CONCLUSIONS AND PERSPECTIVES

We have created a new dataset for the validation of dispersion models that includes third and fourth moments of the concentration PDF, and we have investigated the effects of the source size on the plume concentration fluctuations. While the mean field is not affected by the source dimensions, the higher concentration statistics are highly dependent on source conditions. We showed that in the near field small sources generate higher fluctuations, and that these fluctuations are produced by the plume meandering motion. The intensity of concentration fluctuations decays moving downwind. In the far field, where relative dispersion is the major contribution to fluctuations, the influence of the source size becomes negligible.

The full experimental data set is available on the website: air.ec-lyon.fr.

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