Analysis of concentration fluctuations in a plume emission model

Adrián Roberto Wittwer¹, Acir Mércio Loredo-Souza², Edith Beatriz Camaño Schettini³.

¹Facultad de Ingeniería, UNNE, Resistencia, Argentina, a_wittwer@yahoo.es
²Laboratório de Aerodinâmica das Construções, UFRGS, Porto Alegre, Brazil.
³Instituto de Pesquisas Hidráulicas, UFRGS, Porto Alegre, Brazil.

ABSTRACT

In this work, the intermittency of the dispersion process of an emission plume is studied through a reduced model in a boundary layer wind tunnel. The intermittent concentrations are analyzed by cumulative probability distributions presented in Weibull plots. The source model represents a point gas emission that disperses in a neutrally stable turbulent boundary layer. Distinct conditions are considered which are determined by the degree of the plume buoyancy, the exit emission velocity and the approaching flow velocity. The dispersion process intermittency was found to increase from the plume centreline to the edge extremities near the source emission. These intermittency characteristics for near field decrease for far field regions.

INTRODUCTION

The study of dispersion and pollutant concentration levels discharged in the atmosphere has become a fundamental issue due to the new environmental demands. Nowadays numerous computational works related with dispersion phenomena are being developed. Usually these studies must be validated with experimental results. The high costs of field experimentation lead to laboratory reduced scale models studies. In this context, the boundary layer wind tunnel becomes an important tool. However, it is necessary that the main characteristics of the atmospheric boundary layer and of the dispersion processes be reproduced. Up to now there are no publications regarding experimental studies of atmospheric dispersion performed in South America using reduced scale models, despite the great urban concentrations and the registered atmospheric contamination problems.

In this work, situations of local dispersion were modeled. A single, point emission source was modeled, representing the conditions at a low height chimney and allowing the modification of the plume buoyancy conditions. The analysis of the dispersion process and concentrations was performed considering the isolated source emission in a homogeneous flow. The mean and fluctuating components of the plume concentration were obtained. These results allowed the characterization of the concentration fields. From the density probability functions it was possible to analyze the intermittency of the concentration field.

ANALYSIS OF CONCENTRATION FLUCTUATIONS

The intermittency of a process could be analysed using probability distributions. The probability density function for a dispersion process may take exponential, Gaussian or log-normal, depending on the region of the dispersion plume. This type of distribution can be represented in Weibull format that come from the expression of Weibull distribution,
\[ P(U) = 1 - \exp \left( - \left( \frac{U}{U_{\text{ref}}} \right)^k \right) \]  

(1)

that is used for wind speed data, where \( P(U) \) is the cumulative probability of the mean wind speed, \( U_{\text{ref}} \) a reference wind speed, and \( k_W \) a shape factor [1]. From equation (1) it is possible to obtain:

\[
\ln U = \ln U_{\text{ref}} + \frac{1}{k_W} \ln \left[ - \ln \left( 1 - P(U) \right) \right]
\]  

(2)

The Weibull format is defined using the expression (2) for another type of data. This format is given by a log-log plot of the negative logarithm of the cumulative probability against the number of standard deviation of exceedance. The probability density function of concentration fluctuation data plotted in this Weibull form allows identifying the intermittency characteristics of a dispersion process [2].

The intermittency of a process is defined by some high peaks happened over periods of zero concentration levels. The work of Fackrell & Robins [3] is one of the early wind tunnel studies of concentration fluctuations for dispersion plumes including the analysis of peak values, intermittency, probability density functions and spectra.

The analysis of the concentration fluctuations and the dispersion process intermittency is very important for understanding of the physical phenomenon and for developing of mathematical models. Also it is possible to estimate maximum level concentration when the medium concentration values are relatively low. This laboratory study could be used for the specific analysis of near and half field dispersion problems in neutrally stable atmospheric condition.

It is important to indicate that the time series of concentration fluctuations obtained from laboratory scale model experiments present lower intermittency than full scale measurements [Schatzmann et al., 1997]. Low frequency variations on atmospheric wind direction do not exist in the simulated flow. This behaviour is in accordance with the laboratory medium concentration values higher than field experiment results.

In this work, the analysis of the intermittency was realised using the plot of probability density function of concentration fluctuations in the Weibull format [2], previously mentioned. The slope of cumulative probability distribution plot in this format can represent the process intermittency.

**EXPERIMENTAL DESIGN**

The basic requirement of a wind tunnel dispersion study is the physical simulation of the atmospheric flow. These tests were performed at “Prof. Joaquim Blessmann” [5] closed return boundary layer wind tunnel of UFRGS. Roughness elements mixture devices were used to reproduce a neutrally stable boundary layer.

For similarity reasons based on the Froude number, low velocities are used in these experiments. Fig. 1 shows the nondimensional profiles obtained with the higher velocity flow and two cases with low velocity flow. In the high velocity, at the reference position, the mean velocity \( U_0 \) is approximately 35 m/s, while that for the low velocities the values of \( U_0 \) are 0.85 and 1.91 m/s, respectively. A power law velocity profile with exponent 0.23 is fit to the experimental values. The corresponding values of turbulence intensity are also presented in Fig. 1. As in the case of the mean velocities, the configuration of the profiles is similar, but in this case the values of the turbulence intensity are greater for \( U_0 = 1.91 \) m/s, presenting deviations for
Due to the fact that the local turbulence intensity are presented, the variation is mainly the product of the relative decrease of the mean velocity and the greater calibration error at low velocity.

The emission source model was built with a circular tube of 20 mm diameter and variable height. Figure 2 shows a picture of the wind tunnel model. Pure helium as well as an air-helium mixture are used for the emissions. The wind velocity in the wind tunnel scale was varied between the $U_0$ values of 0.85 and 3.04 m/s to allow the modification of the plume characteristic parameters. The plume characteristic conditions are determined by the nondimensional parameters indicated below. Table 1 presents values of the parameters considered in the plume characterization. The adopted relations and nondimensional parameters are the ratio between the emission and the approaching flow velocities $w_0/U_0$, the emission momentum $\rho_0w_0^2/\rho_aU_0^2$, and the buoyancy parameter defined by $[(\rho_0 - \rho_a)gw_0D_0]/\rho_aU_0^3$. The values of the velocities $w_0$ and $U_0$ correspond to the reduced model values and $D_0$ is the emission source diameter. Conditions (d) and (h) correspond to emissions of mixtures helium-air with density of 0.462 and 0.325 kg/m$^3$, respectively.

The values of the velocities $w_0$ and $U_0$ correspond to the reduced model values and $D_0$ is the emission source diameter.

Conditions (d) and (h) correspond to emissions of mixtures helium-air with density of 0.462 and 0.325 kg/m$^3$, respectively.

For the study of the plume dispersion process, the concentration field was evaluated leeward from the emission source. The measurements were performed by a hot-wire anemometer with an aspirating probe. This probe is composed by the hot wire and a 0.3 mm internal diameter ceramic tube, connected to a vacuum pump, allowing the measurement of instantaneous concentrations [7]. This type of probe produces a wide useful bandwidth of frequency response.
and it allows the evaluation of the plume fluctuating concentration near the source in a turbulent wind [9]. In each point, a one minute sample was taken, at a sampling frequency of 1024 Hz.

Table 1: Characteristic parameters of the plume model

<table>
<thead>
<tr>
<th>Condition</th>
<th>Emission</th>
<th>$w_0$ [m/s]</th>
<th>$U_0$ [m/s]</th>
<th>$\frac{w_0}{U_0}$</th>
<th>$\rho_0w_0^2$</th>
<th>$\frac{(\rho_0 - \rho_a)gw_0D_0}{\rho_aU_0^3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>He</td>
<td>0.56</td>
<td>0.85</td>
<td>0.66</td>
<td>0.060</td>
<td>-0.154</td>
</tr>
<tr>
<td>(b)</td>
<td>He</td>
<td>1.26</td>
<td>1.91</td>
<td>0.66</td>
<td>0.060</td>
<td>-0.031</td>
</tr>
<tr>
<td>(c)</td>
<td>He</td>
<td>0.95</td>
<td>0.85</td>
<td>1.11</td>
<td>0.171</td>
<td>-0.260</td>
</tr>
<tr>
<td>(d)</td>
<td>He - Ar</td>
<td>0.75</td>
<td>0.85</td>
<td>0.88</td>
<td>0.278</td>
<td>-0.154</td>
</tr>
<tr>
<td>(e)</td>
<td>He</td>
<td>0.56</td>
<td>3.04</td>
<td>0.18</td>
<td>0.005</td>
<td>-0.003</td>
</tr>
<tr>
<td>(f)</td>
<td>He</td>
<td>0.95</td>
<td>3.04</td>
<td>0.31</td>
<td>0.013</td>
<td>-0.006</td>
</tr>
<tr>
<td>(g)</td>
<td>He</td>
<td>0.56</td>
<td>1.91</td>
<td>0.29</td>
<td>0.012</td>
<td>-0.014</td>
</tr>
<tr>
<td>(h)</td>
<td>He - Ar</td>
<td>1.45</td>
<td>1.91</td>
<td>0.76</td>
<td>0.145</td>
<td>-0.031</td>
</tr>
</tbody>
</table>

The results obtained in the tests are presented as concentration coefficient $K$ and intensity of the concentration fluctuations $I_c$ profiles, being $K = \frac{CU_0H^2}{Q_0}$ and $I_c = \frac{\sigma_c}{C}$, $C$ and $\sigma_c$ are the mean concentration and the standard deviation of the fluctuations, respectively, $Q_0$ is the flow emission, $U_0$ is the wind velocity corresponding to the emission height and $z$ is the vertical coordinate measured from the wind tunnel floor.

RESULTS

Instantaneous concentrations were measured in vertical profiles located in several distances $x/H$, measured from the emission. Coordinate $x$ indicates the distance from the measurement point and the height of the chimney is $H = 250$ mm. The concentration mean and rms values were obtained
for each point. Figure 3 presents the vertical profiles of the concentration coefficient $K$ and the intensity of the concentration fluctuations $I_C$ for condition (a), related to the positions $x/H = 0.33$, 0.66 and 1.00. Similar analysis was performed for other conditions and leeward positions $x/H$ [10].

![Figure 3: Concentration profiles K and I_c, condition (a) for x/H = 0.33, 0.66, 1.00.](image)

Examples of time series of the concentration fluctuations are shown in figure 4. Digitized sample points as a function of time near the plume upper edge ($z/H = 1.26$) and near the plume centre ($z/H = 1.12$) in condition (a), at the downstream position $x/H = 0.33$. The concentration appears to be intermittent with high-concentration peaks separated by intervals of zero concentration, near the plume edge. Peak concentration values of $1 \times 10^5$ in parts per million (ppm) by mass are obtained. Lower intermittency is observed near the centre plume and the peak concentration values are about $2 \times 10^5$ ppm. Characteristics of concentration fluctuations are similar to the measurements obtained by Poreh & Cermak [11] in wind tunnel experiments.

![Figure 4: Time series of concentration fluctuations at positions x/H = 0.33, z/H = 1.26 (plume upper edge) and z/H = 1.12 (plume centre) for condition (a).](image)
The probability density function (p.d.f.) of concentration fluctuations was obtained for each time series measured. Figure 5 represents the cumulative probability density functions of concentration fluctuations at distances \( x/H = 0.33 \) and \( x/H = 0.66 \) downstream for condition (a). At position \( x/H = 0.33 \), cumulative p.d.f. of concentration measured at three different heights \( z \) are shown. Near the plume centre \( (z/H = 1.12) \), the slope of the probability distribution in Weibull format is much steeper than that near the plume edge. A decrease of this slope indicates an increase in the intermittent behaviour. Intermittency of concentration is greater at the plume upper edge \( (z/H = 1.26) \) than at the plume lower edge \( (z/H = 0.96) \). This variation of the intermittency characteristics at plume extremity regions involves a distortion of the Gaussian behaviour previously observed in the analysis of mean concentration values for near field. It is possible to assume this different behaviour like a product of different buoyancy effects upwards and downwards of the plume centreline.

A more detailed description is shown at position \( x/H = 0.66 \). Again the slope of the cumulative p.d.f. of concentration is much steeper near the plume centre. The slope decrease from 1.09 at central position \( (z/H = 1.16) \) to 0.061 at upper edge \( (z/H = 1.42) \). With respect to the lower edge \( (z/H = 0.90) \), a decrease of this slope is observed but only to 0.51. Therefore, the behaviour of the previous position happens again. The linear fit and the corresponding expressions are indicated in the graphic.

The cumulative p.d.f. of concentration at positions \( x/H = 2.00 \) and \( x/H = 3.80 \) for condition (a) are presented in Figure 6. At location \( x/H = 2.00 \) downstream are shown the measurements corresponding to five different height. The point \( z/H = 1.34 \) is located at the plume centre, the points \( z/H = 1.02 \) and 1.18 at the lower region and points \( z/H = 1.62 \) and 1.86 at the upper region of the plume. It is possible considering this downstream location like a near-half field position. General characteristics of the intermittency stay like the previous positions analysed but a decrease of intermittent behaviour take place at the plume upper edge.

Results of three measuring points are analysed at position \( x/H = 3.80 \). This location could be considered half-far field. A great decrease of the intermittency process is observed at this position and consequently the slope of the probability distribution in Weibull format is very similar at different positions. The slope is 1.10 near the plume centre, 1.02 at the upper edge and 1.22 at the lower edge of the plume. Therefore, the intermittency is a little smaller at the lower region than at the plume centre.

Figure 7 presents the results for condition (b) with a change of incident wind velocity and so, the inertial effects are greater than that for condition (a). Locations \( x/H = 0.60 \) e 1.80 were analysed and the results are presented for three different positions, near the upper edge, the lower edge and the plume centre. The position of the plume centreline indicates the greater inertial effects with respect to condition (a). Particularly at position \( x/H = 0.60 \), the behaviour is quite similar to that observed for condition (a), but the intermittency is a little smaller near the upper edge and a little greater near the lower edge. In the other hand, the decrease of the intermittency downstream is a bit lower than for condition (a).

In the Figure 8 are shown plots of cumulative p.d.f. for near field concentrations \( (x/H = 0.33) \) corresponding to conditions (c) and (d). General behaviour is very similar on both cases, but it is possible to notice a bit higher intermittency at plume upper region and a little smaller intermittency at plume lower region for condition (d).

Results of measurements for conditions (g) and (h) at location \( x/H = 0.60 \) are shown in Figure 9. The behaviour for condition (g) is quite similar to that obtained for conditions (a) and (b). The linear fit corresponding to the values obtained for this condition near the centre and the extremities of the plume are indicated in the graphic. For condition (h), the emission is a mixture
of helium-air. The cumulative p.d.f. obtained for this condition are comparable with the p.d.f. corresponding to conditions (a) and (b) at locations \( x/H = 0.66 \) and 0.60, respectively.

Figure 5: Cumulative probability density functions of concentration fluctuations at distances \( x/H = 0.33 \) and \( x/H = 0.66 \) downstream - condition (a).

Figure 6: Cumulative probability density functions of concentration fluctuations at distances \( x/H = 2.00 \) and \( x/H = 3.80 \) downstream - condition (a).

Figure 7: Cumulative probability density functions of concentration fluctuations at distances \( x/H = 0.60 \) and \( x/H = 1.80 \) downstream - condition (b).
Figure 8: Cumulative probability density functions of concentration fluctuations at distance $x/H = 0.33$ downstream - conditions (c) and (d).

Figure 9: Cumulative probability density functions of concentration fluctuations at distance $x/H = 0.60$ downstream - conditions (g) and (h).

CONCLUSIONS

The dispersion process and the concentration fluctuation fields were analyzed considering an isolated source emission. The intermittency at different dispersion plume regions has been analyzed using cumulative probability distributions. The slope of the plot in Weibull form was used to determine the intermittency of the concentration.

Near the emission source, the process is highly intermittent at the upper edge extremity of the plume decreasing to the centerline. The intermittency is greater at the plume upper edge than at the plume lower edge. This intermittent behaviour of the plume extremities decrease for far field regions. When the inertial effects increase, the observed decrease of the intermittency downstream is a bit lower. In general, variations of wind speed, efflux momentum and buoyancy effects were found to produce a little change on the intermittency characteristics near the emission.

This analysis was realised using only probability distributions functions. The study of the dispersion process intermittency will be complemented with the spectral analysis of the concentration fluctuations in a next work.
ACKNOWLEDGEMENT
The authors are grateful to CAPES for the financial support.

REFERENCES


