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WATER CHANNEL INVESTIGATION OF FLOW AND DISPERSION IN STREET CANYONS

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Abstract: This paper describes experiments conducted in the water channel for studying the turbulent dispersion of a passive pollutant emitted by a line source located at the bottom of a street canyon. Velocity and pollutant concentration fields have been measured simultaneously in correspondence of an arrangement of two-dimensional obstacles that simulate a street canyon with aspect ratio unity. From the instantaneous values of the pollutant concentration, high-spatial resolution maps of mean, standard deviation and skewness factor of the concentration field have been determined both within and outside the canyon.

Key words: *Street Canyon, Concentration fluctuations, Water channel, Line source, Concentration peaks.*

INTRODUCTION

Numerous studies have been performed during the last decades in order to improve our understanding on wind flow and pollutant dispersion in urban environments. Vehicular traffic is the major source of pollutants in cities and their concentration depends also on the shape of the buildings surrounding the street. It is therefore of great interest to analyse pollutant dispersion in the street canyon, which can be considered as the simpler entity representing real situations. A number of laboratory experiments have been dedicated to this issue, both for two-dimensional (see for example Caton et al., 2003; Salizzoni et al., 2011; Di Bernardino et al., 2015) and three-dimensional configurations (Takimoto et al., 2011, among others). These studies have shown the role played by the interface layer forming between the flow within the canyon and the outer flow and, at the same time, how its dynamics govern exchanges of mass and momentum, which play a central role in pollutant exchange rates in street canyons (Liu et al., 2005).

An important goal in pollutant dispersion studies is the knowledge of concentration fluctuations. They are useful, for example, to determine the range of the expected values of concentration for microscale dispersion and to better simulate chemical reactions, which depend on the instantaneous concentration, rather than the mean (for recent developments on this issue see for example Amicarelli et al., 2001 and 2012). One of the main problems encountered in flow and dispersion studies conducted by means of laboratory (as well as field) experiments is how to measure flow velocity and concentration simultaneously, being the latter an essential issue in determining important quantities such as the turbulent concentration flux and eddy diffusivity of mass. Besides, given the strong spatial inhomogeneity of street canyon flows, experimental campaigns based on single point measurements rarely allow an exhaustive description of the phenomena. This is the main motivation of this work, which reports some preliminary results on measurements of concentrations of a pollutant emitted at surface level from a line source located within a two-dimensional street canyon with aspect ratio H/W=1. The experiments, conducted by using a water channel, show the capability of the apparatus in determining spatial inhomogeneities of the mean, the standard deviation and skewness of the pollutant concentration both within and outside the canyon.

EXPERIMENTAL SETUP

The experiments are performed using a closed-loop water channel facility (Figure 1; details on the experimental apparatus can be found in Di Bernardino et al., 2015). The channel is 35 cm high, 25 cm wide, 740 cm long, and a constant head reservoir feds the flume. A floodgate allows regulating the water depth and, therefore, the water velocity. A series of parallelepipeds (made by PVC) of square section B=H=2 cm and length (L) equal to the channel width are glued onto the channel bottom (Figure 2). Preliminary experiments showed that L is long enough to ensure that the flow in the central section of the channel is two-dimensional and that the influence of the vertical walls is negligible. The test section is located nearly 500 cm downstream of the inlet, where the boundary layer is fully developed. The water depth is 16 cm and the free stream velocity is 34 cm s^{-1}. The Reynolds number of the flow is nearly 50000. A line source of dye (rhodamine) is located at the bottom of the cavity in correspondence of the canyon centre (Figure 2). The tracer reaches the source through a thin silicone tube, connected to a constant head reservoir that guarantees the discharge of the tracer with a constant rate.

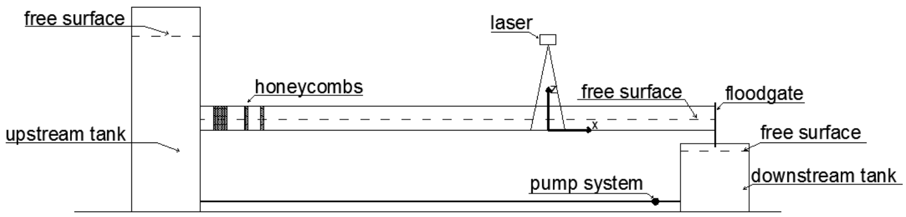

Figure 1. Side view of the experimental apparatus. The x-axis refers to the longitudinal axis of the channel, while the z-axis is parallel to the vertical

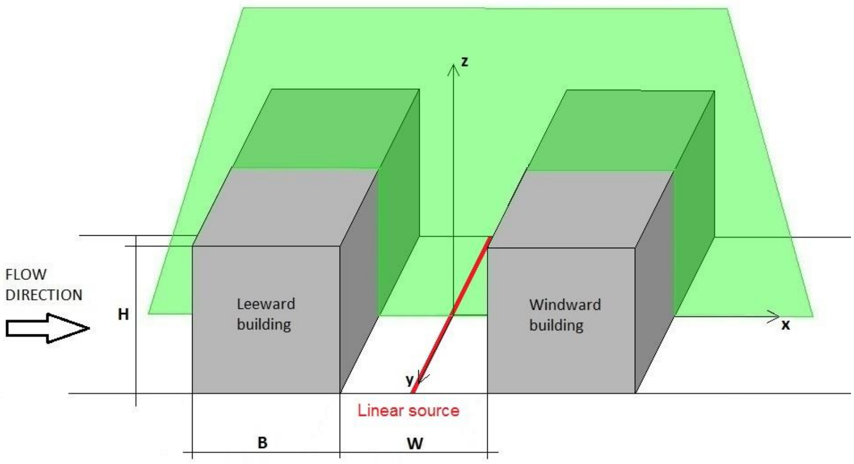

Figure 2. Sketch of the modelled street canyon. The vertical plane in green represents the laser beam.

Velocity and concentration fields are measured simultaneously using an image acquisition system consisting of two (synchronized) cameras: the first one permits the velocity field to be evaluated by a feature-tracking algorithm based on image analysis (see for details Di Bernardino et al., 2015), while the second camera is used for the concentration measurements via laser-induced fluorescence (LIF). The cameras (1280×1024 pixels resolution) acquire at 250 frames per second, and a thin laser light sheet (wavelength: 532 nm) illuminates the test section. The two cameras are aligned vertically, to frame the area of interest (i.e. the canyon) and to reduce as much as possible image distortion. The rhodamine is a non-reactive fluorescent dye that, excited at 532 nm (green), emits at 587 nm (red). The light emitted by the rhodamine is captured by the camera equipped with a filter tuned to 587 nm to allow only the fluorescence and not the laser light to pass. The dye concentration at a given pixel (directly proportional to the fractional volume of the dyed fluid) is assumed proportional to the measured luminosity. An affine transformation that best maps the features viewed from one camera on those recognized by the second camera is used to map the concentration field onto the velocity field. For details on this procedure, see Monti et al. (2007). The framed area is rectangular (85 mm long and 74 mm high), lying in the vertical mid-plane of the channel. The velocities measured in each time instant with the feature-tracking algorithm are interpolated on a regular grid by Gaussian averaging (Cenedese et al., 2000). The resulting spatial resolution is 1 mm; the one of the concentration field is nearly 0.1 mm. The experiments last 80 s and, therefore, 20000 velocity and concentration fields, taken simultaneously, are used to calculate the statistical moments.

RESULTS

Before proceeding with the analysis of the statistical moments of the pollutant concentration, it is useful to examine some of the main features of the flow. Figure 3 shows the instantaneous velocity (arrows) and the normalized concentration fields (colours) taken in correspondence of the canyon in a phase of the flow when most of the pollutant emitted by the line source is contained within the canyon. The normalized concentration, C*(x,z,t), refers to the ratio between the actual concentration and the (constant) value of the concentration at the source. It is apparent the presence of two main flows, i.e. the external boundary layer and the recirculating eddy inside the canyon (for a detailed description of the flow occurring for the same geometrical arrangement see Di Bernardino et al., 2015). Pollutants remain trapped within the canyon and tend to recirculate several times, carried by the main eddy. The time needed by a fluid particle to travel the whole eddy is 3-4 s, while the time needed by a fluid particle to cross the canyon top is nearly 0.2 s. The interface between the inner and the outer regions, i.e. the shear layer, is characterized by large velocity gradients that give rise to Kelvin-Helmholtz type instabilities governing exchange of mass and momentum between the inner and the outer flow. These play an important role in determining the characteristics of the overlying roughness sublayer, including vertical profiles of wind and temperature (Pelliccioni et al., 2012).

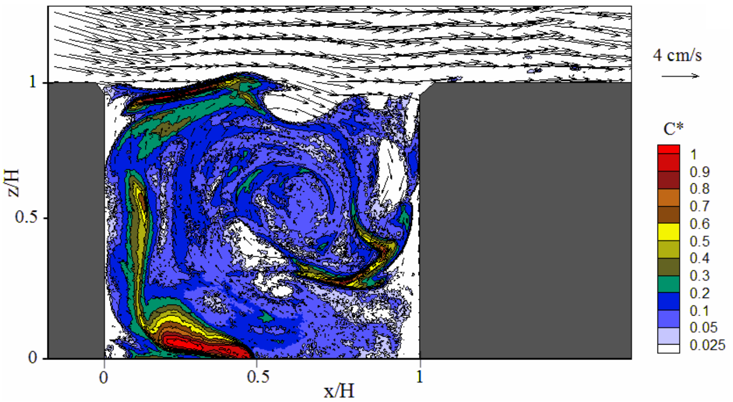

Figure 3. Map of the instantaneous velocity (vectors) and concentration (colours) fields in a phase when the recirculating eddy inside the canyon captures all the pollutant.

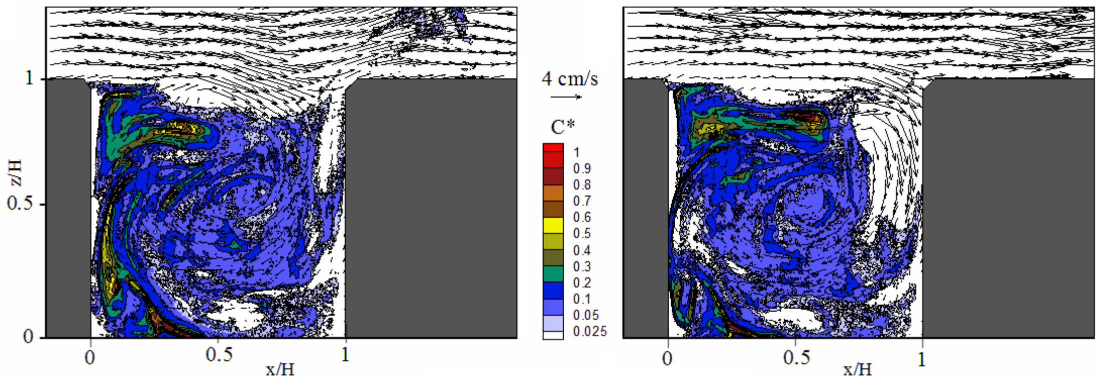

Figure 4. Maps of the instantaneous velocity (vectors) and concentration (colours) fields during the sweep mode. The right panel refers to the flow present 0.1 s later than that shown in the left panel.

Figure 4 shows examples of the so-called sweep mode (see for example Takimoto et al., 2011), responsible of intrusion of fresh fluid from the outer layer into the canyon (the two pictures refer to instants of time nearly 0.1 s away). Examples of the counterpart of the previous feature, i.e. the ejection mode, are depicted in Figure 5, where is evident the expulsion of pollutants from the right part of the canyon top. Both these modes are related to the shear layer flapping and appear with periodicity of nearly 0.5 s. The temporally averaged mean concentration field is plotted in Figure 6, which evidences how the region next to the wall of the windward building is characterized by lower concentration values. This contrast with the findings of Caton et al. (2003), who found a fairly uniform concentration field inside the cavity. The region of nil concentration that appears in the upper part of the leeward building is a signature of the secondary vortex that forms there.

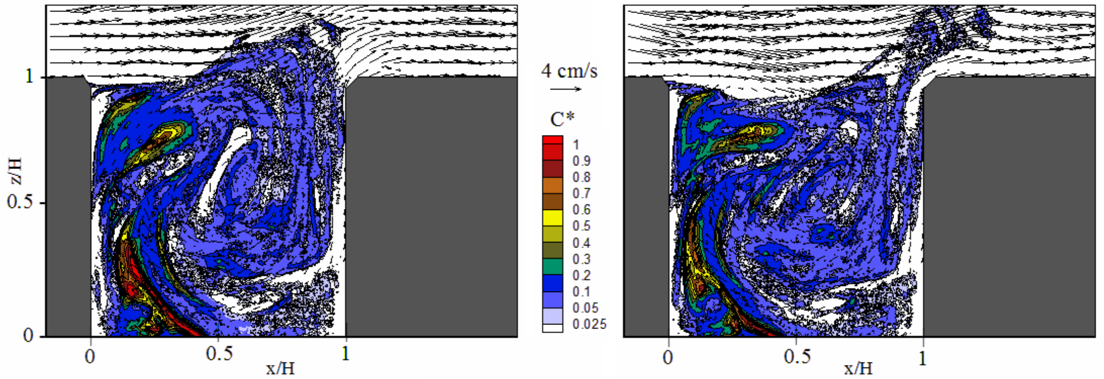

Figure 5. As in Fig. 4, but for the ejection mode.

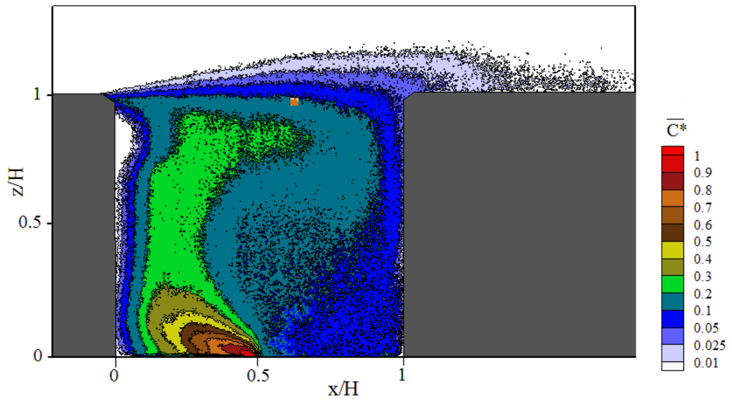

Figure 6. Map of the normalized mean concentration.

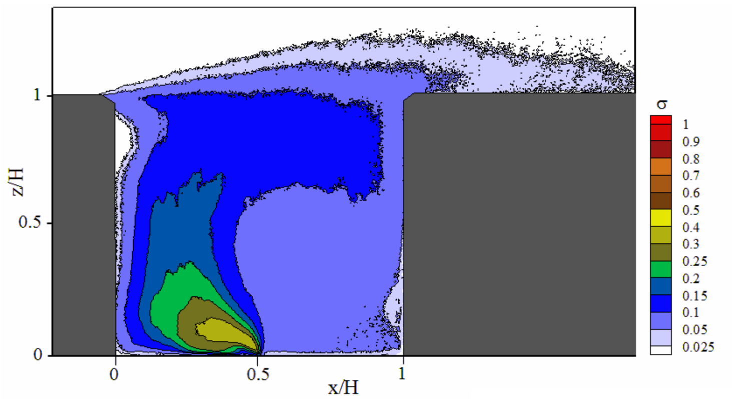

Figure 7. Map of the standard deviation of the normalized concentration.

Figure 7 depicts the map of the standard deviation of the normalized concentration. It behaves similarly to the average, showing larger values close to the source and in the left region of the canyon. Finally, the skewness factor (Figure 8) shows both positive and negative values, the latter being concentrated close to the source, where the plume oscillation produces a non-negligible asymmetry of the probability density function of the concentration. Note the large, positive values outside the canyon, which are ascribable mainly to the small values of the standard deviation present in the outer layer.

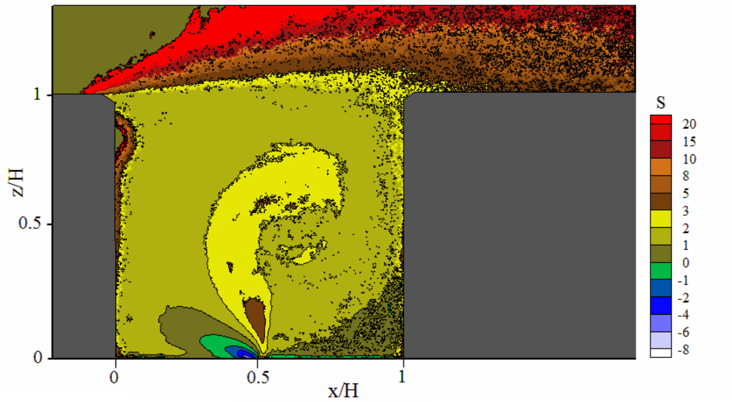

Figure 8. Map of the concentration skewness.

CONCLUSIONS

Simultaneous, whole field measurements of velocity and concentration have been employed to investigate experimentally a vertical plane in the mixing of a passive pollutant emitted from a line source simulating vehicular traffic. Some stages of the flow field, such as the sweep and ejection modes, have been visualized and discussed. We also provided high-resolution measurements of the average concentration field, as well as standard deviation and skewness of the concentration. The method seems to be well suited to acquire important flow variables such as the turbulent concentration flux.

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