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Pollutant fluxes in two-dimensional street canyons

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ABSTRACT

The turbulent dispersion of a passive tracer emitted by a line source simulating vehicular traffic in an idealized urban canyon in neutral conditions is studied in the water channel by means of simultaneous measurements of velocity and concentration fields. The experiments are conducted for two geometrical arrangements of two-dimensional obstacles reproducing the skimming flow (AR = 1) and the wake-interference regime (AR = 2), where AR is the canyon aspect ratio. The results show a strict connection between the dynamics of the shear layer developing at the top of the canyon and the vorticity field. For AR = 1, it is found that the shear layer flaps upwards and downwards according to two different frequencies. The greatest of them matches the vortex shedding frequency as measured at the canyon top, while the lower is comparable to H/u_* (H is the building height and u_* a reference friction velocity). The shear layer flapping modulates in time the pollutant exchange rate between the canyon and the outer layer. The different characteristics of the shear layer found for the two flow regimes also explain the larger pollutant re-entrainment observed for AR = 1, which turns out to be greater than the emission rate at the source. Sweep and ejection modes are identified via quadrant analysis and used to quantify the weights of the factors involved in the turbulent exchanges of tracer and momentum between the canyon and the outer layer. It is found that the venting of polluted fluid at the canyon top increases substantially passing from AR = 1 to 2, while an opposite trend is observed for the entrainment of polluted fluid. The vertical flux of pollutant at the canyon top for AR = 2 is largely of turbulent nature, with the contribution of the mean flux being practically negligible. On the other hand, the latter becomes comparable or even exceeds the magnitude of the turbulent flux when AR = 1. The maps of the first three statistical moments of the pollutant concentration for the two geometrical arrangements are also reported and discussed.

1. Introduction

The complex building arrangements, the extremely variable locations of the pollutant sources as well as the incomplete knowledge of the turbulence processes characterizing urban canopy flows make the investigation of flow and dispersion of contaminants in urban canopies a very difficult task (Fernando, 2010; Barlow, 2014; Buccolieri et al., 2015).

Numerous studies have shown the importance of the building geometry on the microscale turbulence and the way the latter strongly affects pollutant dispersion (e.g. Liu et al., 2004). Among the infinite set of building geometries found in real cities, the two-dimensional street canyon can be considered as a basic morphological unit of the urban texture. It is defined as the space above a narrow street edged by series of parallel, tall buildings. Hussain and Lee (1980) showed that for this kind of geometrical configuration the flow can be classified based on the canyon aspect ratio, AR = W/H, where W and H are the spacing between two adjacent

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buildings and their average height, respectively. Under isothermal conditions, Oke (1987) identified the skimming flow (AR $\lesssim$ 1.5), where a single vortex forms within the cavity, the wake-interference regime (1.5 $\lesssim$ AR $\lesssim$ 2.5), in which two counter-rotating vortices develop in the street canyon, and the isolated roughness regime (AR $\gtrsim$ 2.5), where the interaction between individual buildings is weak or absent.

In the case of the skimming flow or wake-interference regime and wind blowing perpendicularly to the street axis, the flow within the canyon separates from that above it. This causes poor canyon ventilation, even when the external winds are strong, and pollutant stagnation. As a result, pollutants emitted by vehicular traffic at street level remain trapped within the cavity, causing high concentrations at pedestrian level. This separation is one of the main causes of air quality deterioration in cities and is partially governed by the shear layer at the canyon top, which plays a key role in the exchange of air and scalars between the canopy and the overlying region. The shear layer forms because of the large velocity gradients occurring at the canopy top. These give rise to Kelvin-Helmholtz type instabilities, which govern mass, energy and momentum exchange rates between the inner and the outer flow. Louka et al. (2000) conjectured that such instabilities cause the vertical flapping of the shear layer that, in turn, regulates the intrusion of fresh fluid from the outer layer into the canyon and, vice-versa, expulsion of pollutants from the canyon into the outer flow (see also Takimoto et al., 2011). Salizzoni et al. (2009a, 2011) showed by means of wind-tunnel measurements how the shear layer dynamics are influenced by turbulent kinetic energy fluxes from the external flow which, in turn, depends on the oncoming boundary layer.

Analysis on pollutant fluxes had come mainly from large eddy simulations (LES). For example, Liu et al. (2005) investigated fluxes of scalars emitted by a line source placed at the bottom of the canyon for different AR values. They found that the amount of pollutants trapped within the canyon increases as AR decreases, particularly at ground level. Besides, they showed that gradient diffusion models are intrinsically unable to predict pollutant dispersion with reasonable accuracy. More recently, Li et al. (2010, 2016) investigated the effects on flow and pollutant transport of the stratification for a two-dimensional array of obstacles with AR = 1, while O'Neill et al. (2016) analyzed both the statistical moments of the pollutant concentration and the vertical component of the turbulent pollutant flux, focusing on their trends at the canyon top.

Owing to intrinsic problems related to the employment of intrusive sensors, only few investigators studied pollutant fluxes in canopy flows experimentally. The main difficulty is to measure simultaneously velocity and scalar concentration fields with high spatial and temporal resolution as well. Therefore, most of the studies that have been reported so far essentially concern measurements conducted in few points of the domain (Kastner-Klein and Plate, 1999; Barlow et al., 2004). In recent years, the use of image analysis techniques has permitted the determination of turbulent fluxes of scalars in the water channel or in the wind tunnel (see e.g. Vinçont et al., 2000; Dezső-Weidinger et al., 2003; Monti et al., 2007; Tomas et al., 2017). Nevertheless, several aspects of the flow structure are still unknown and need to be clarified in order to improve knowledge about pollutant dispersion in urban environments. For example, it would certainly be of interest to know how pollutant and momentum fluxes at the canyon top depend on the canyon aspect ratio.

In this work, we aim to analyze the dispersion mechanisms of a passive pollutant discharged into a two-dimensional urban canyon − reproduced in a water-channel facility − by measuring simultaneously velocity and scalar concentration fields with high temporal and spatial resolutions. Both the skimming flow and wake-interference regimes are analyzed and particular attention is paid to turbulent momentum and scalar fluxes within the cavity, especially at the shear layer.

The paper is organized as follows. Section 2 gives a description of the laboratory facility and the acquisition technique, while Section 3 presents the results obtained for the two geometries investigated. Both the spatial distribution of the first three statistical moments of the tracer concentration and the maps of the vertical momentum and tracer fluxes are presented, focusing on their trends calculated at the canyon top. Finally, the Pollutant Exchange Rate (PCH) and the Air Exchange Rate (ACH), two useful parameters introduced by Liu et al. (2005), are also determined and discussed. In Section 4, the most important conclusions of the work are summarized.

2. Experimental setup and measurement technique

The experiments are performed in a recirculating water channel located at the Hydraulic Laboratory of the University of Rome – La Sapienza. This water channel has a rectangular cross section of 0.35 m height and 0.25 m width and a length of 7.40 m. To observe the flow visually, the lateral sides of the tank are made of transparent glass. A constant head reservoir feeds the flume and a floodgate, located at the end of the channel, regulates the water depth and, therefore, the water velocity. Three honeycombs are positioned at the opening section of the channel to minimize unwanted effects due to the inlet system. To recreate the naturally grown atmospheric boundary layer in the water channel, the roughness of the channel bottom is increased by means of randomly distributed pebbles (average diameter ≈ 5 mm), glued onto the bottom (Fig. 1). Downstream of the pebbles, a series of evenly spaced parallelepipeds with square section B = H = 20 mm (here B indicates the building width) and length equal to the channel width are glued onto the channel bottom, normally to the streamwise velocity (for further details on the experimental setup see Di Bernardino et al., 2015a).

Two geometrical configurations are investigated by varying the distance (W) between the obstacles. In particular, the skimming flow and the wake-interference regime are simulated by setting W = 20 and 40 mm to obtain street canyons with AR = 1 and 2, respectively. The test section is located nearly 5 m downstream of the inlet, where the boundary layer is fully developed and the water depth is 0.16 m. The Reynolds number of the flow, $Re = UH/\nu$, based on the free stream velocity, $U = 0.33\ m\,s^{-1}$, is nearly 50,000 ($\nu = 10^{-6}\ m^2\,s^{-1}$ is the kinematic viscosity of water), while the roughness Reynolds number, $Re_* = u_*H/\nu$, is 380 for AR = 1 ($u_* \approx 0.019\ m\ s^{-1}$ measured within the constant flux layer) and 540 for AR = 2 ($u_* \approx 0.027\ m\ s^{-1}$). Therefore, both the simulated large-scale structures and the mean flow can be considered as being independent of *Re* (fully rough wall regime, see Snyder (1972); Uehara et al. (2003). For additional information on the *Re* independence of the flow simulated in the present water channel see Di