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Effect of short–time variations of wind velocity on mass transfer rate between street canyons and the atmospheric boundary layer

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ABSTRACT

2D URANS CFD simulations were conducted to study the effect of short–time variations of wind velocity on mass transfer rate between street canyons and the atmospheric boundary layer (ABL). A street canyon with a height–to–width ratio (aspect ratio) of three was considered as a case study. The study is of practical interest since it illustrates a skimming flow regime, the regime where pollutants are less effectively exchanged between the canyon and the above atmosphere, typically found in many urban areas in Mediterranean countries. Short–time variations of wind velocity magnitude were simulated assuming a sinusoidal function with average magnitude = 4 m s^{-1}; amplitude ±2 m s^{-1} and period from 1 to 40 s, and subsequently with short–time averaged (0.1 s, 1 s and 10 s) real world data measured with an ultrasonic anemometer (50 Hz). Mass transfer rate between the canyon and the ABL was evaluated as the rate of reduction of spatially averaged concentration of a passive pollutant, carbon monoxide (CO), in the street canyon. Results show that mass transfer rate increases with the frequency of short–time variations. In CFD studies pertaining to pollutant dispersion in street canyons, wind hourly average velocity is usually assumed as a reference value to simulate real world cases. Our results show that this input data must be completed with additional information about the extent of variation in wind intensity and its frequency in the hour.

Keywords: *Street canyon, mass transfer, modeling, CFD, short–time variations*

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1. Introduction

Accurate evaluation of the mass transfer rate between urban roads and the atmospheric boundary layer (ABL), together with evaluation of vehicular emission rates, is crucial for reliable assessment of air quality (concentration of pollutants at street level) in urban areas. However, although mass transfer from such roads to the ABL has been studied more than two decades, complete knowledge of the phenomenon has yet to be achieved.

Starting from the first papers on this topic, real urban roads were idealized as a single road of infinite length delimited by buildings of the same constant height on both sides of the road and with wind direction perpendicular to the street axis. This geometry is that of a cavity termed "ideal street canyon". The building height–to–street–width aspect ratio (AR) was assumed as the key geometrical parameter defining the building geometry and the flow patterns.

Oke (1987) characterized the flows in street canyons into three regimes, namely isolated roughness (AR<0.3, wide street), wake interference (0.3≤ AR ≤0.7), and skimming flow (0.7<AR, tall buildings or narrow streets). CFD studies were conducted from the 1990s onwards (Sini et al., 1996) to obtain the flow field inside the canyon and information about pollutant dispersion inside the canyon and mass exchange with the ABL.

Reliable evaluation of mass transfer between the canyon and the ABL is essential for the prediction of concentration levels inside the street canyon. Indeed, it has been studied by several authors: Bentham and Britter (2003) developed a model to characterize in–canopy velocity and to evaluate average exchange velocity between in–canopy and above–canopy flows; Barlow et al. (2004) measured the mass transfer coefficient observing naphthalene sublimation in a lab–scale array of street canyons for *H*/*W*=0.25, 0.6, 1 and 2. Hamlyn and Britter (2005) simulated the processes of flow and exchange within obstacle arrays using the CFD code FLUENT and discussed the transfer of mass between the canopy and the air above it in terms of the exchange velocity. Salizzoni et al. (2009) studied the mass exchange between a street canyon and the external atmospheric flow by means of wind tunnel experiments. They developed a two–box model and evaluated a mass transfer velocity. Murena et al. (2011) in a 2D CFD study, developed a box model for deep street canyons. In this case an overall mass transfer velocity was defined to quantify the overall mass transfer process from the bottom volume of the canyon to the ABL.

In recent years the large eddy simulation (LES) approach has been frequently applied to this topic. Chung and Liu (2013) in a LES study on a 2D idealized canyon evaluated ventilation and pollutant removal, determining the following parameters: air exchange rate (ACH) and pollutant exchange rate (PCH).

The mass exchange between the air in the street canyon and the atmosphere above takes place through the shear layer which forms between the cavity and the ABL (Caton et al., 2003). Although published studies generally make reference to an external velocity to characterize the mass transfer rate, many authors agree with the evidence that turbulent transport dominates the mass exchange. It is widely considered that the instantaneous (turbulent) contribution to mass transfer velocity is higher than the mean (advective) contribution. However, the latter is not negligible. The advective contribution may be considerable when the building height is not uniform (Hamlyn and Britter, 2005). Caton et al. (2003) observed that mass transfer depends both on an external reference velocity and on the structure of the incoming turbulence. Further, by contrast, Salizzoni et al. (2009) observed that mass transfer appears to be entirely governed by the fluctuating component of the turbulent flow and unaffected by the magnitude of the mean recirculating flow within the canyon.

Results of LES show that in all three regimes (i.e. isolated roughness, wake interference and skimming flow) street canyon ventilation is dominated by turbulent transport (Chung and Liu, 2013). Indeed, roof–level turbulence mainly governs the ventilation performance of street canyons, contributing up to 80–90% to the total air exchange rate (Chung and Liu, 2013). The flow in the ABL above in correspondence of the canyon cavity is also characterized by strong unsteadiness (Castro et al., 2006; Takimoto et al., 2011) generating intermittent coherent turbulent structures which penetrate the street canyon, affecting mass transfer. Michioka and Sato (2012) observed in LES on a two–dimensional street canyon with an aspect ratio of one that coherent structures of low–momentum fluid, generated close to the plane of the roof, contributed to pollutant removal. An LES model of the transport and dispersion of passive scalars in a 2D street canyon was developed for H/W=1/3, 1/2, 2/3, 1/1, 3/2, and 2/1 (Cai et al., 2008). Results of simulations were validated against several datasets of wind tunnel experiments.

In all the studies reported above, average wind velocity in the ABL is assumed constant with time. To compare results of simulations with real world data it is common to make reference to hourly average wind speed data. The choice of one hour as the averaging time originates from ambient air quality regulations adopted in many countries (EC, 2008; U.S. EPA, 2013) where one hour is the shortest averaging time during which pollutant concentrations have to be measured.

Short–time resolution of wind data (direction and intensity) can be obtained by using an ultrasonic anemometer with a measurement frequency generally in the range 10–50 Hz. Xie (2011) reports 30 s and 60 s averaged time wind data collected by an ultrasonic anemometer showing how wind magnitude and direction can vary in a time interval of one hour by ±36% and ±22° respectively (but larger variations can be frequently observed). The paper by Xie (2011) shows how wind magnitude and direction can fluctuate around the hourly average or follow an increasing or decreasing trend in some fractions of the hour. However, it is evident that real wind deviates from the one–hour average both in magnitude and in direction.

Some measurements with a 50 Hz triaxial ultrasonic anemometer were carried out at roof top level in the centre of Naples (Spano, 2011). Wind variations were extremely fast and generally random around a time–averaged value. In some cases a trend with time (increasing or decreasing) was observed. An example of ultrasonic anemometer measurements of the horizontal wind magnitude (Spano, 2011) at roof top level is reported in the Supporting Material (SM).

The effect of short–time wind variations on the mass exchange between the urban canopy or a single street canyon and the ABL has been rarely considered. Xie (2011) used 30– and 60 s averaged wind data measured at 190 m above street level by an ultrasonic anemometer (10 Hz resolution) to simulate real wind conditions in an LES simulation of the Marylebone Road. Since it was a 3D simulation both wind intensity and direction variations were considered. A comparison of 3–min averaged concentration at a selected site showed fairly good agreement between simulation results and real data when 30– and 60 s averaged real wind data were adopted in place of steady wind conditions (Xie, 2011).

In this paper the results of 2D URANS CFD simulations in an ideal deep street canyon assuming a time–dependent inflow wind velocity are reported. The time dependence of inflow wind velocity was first described assuming a sinusoidal function with average value v=4 m s^{-1} and amplitude ±2 m s^{-1}. The time period was varied from 1 to 40 s. Then real world data measured with an ultrasonic anemometer placed at the roof top level in the centre of Naples were time–averaged (0.1 s, 1 s and 10 s) and used to simulate wind velocity in the ABL.

The correct choice of the turbulence simulation method is a critical issue in CFD (see for instance Spalart, 2000). LES calculations at high Reynolds numbers (i.e. >10^{6}) require strong, sometimes prohibitive, computational effort. In fact, increasing the Reynolds number the mesh size required for an accurate LES calculation becomes almost comparable to the mesh size required for a Direct Numerical Simulation (see for instance Pope, 2000). On the other hand, RANS–URANS pros and cons are also well known. That said, in the last two decades RANS–URANS have been successfully applied in complex external flows (see for instance Durbin, 1995; Iaccarino et al., 2003; Do et al., 2010, Catalano and Tognaccini, 2010) and in wash–out simulations (Murena et al., 2011; van Hoff and Blocken, 2013), demonstrating that accurate URANS calculation is able to recover reasonable results. One of the cases where URANS methods are particularly effective at providing time–accurate prediction is when the unsteadiness is externally imposed, provided that the external imposed time scale is far enough from the time scale of turbulent fluctuations. This is the main reason why we chose such methodology together with the consideration that the large number of simulations required in the present study were difficult to perform by LES methods. That said, in order to validate the URANS calculations, an LES simulation was also performed in one of the cases studied and compared with URANS result in terms of street canyon wash–out time.

Geometry and boundary conditions of simulations were selected in order to study a case of practical interest. Indeed, the aspect ratio was set at 3, which is typical of many urban areas in Mediterranean countries governed by a skimming flow regime, where pollutants are less effectively exchanged between the canyon and the above atmosphere. Average wind velocity was set at 4 m s^{-1}, a value very frequently occurring in the Mediterranean area.

The aim of this study was to obtain information on to what extent mass transfer rate between urban street canyons and the ABL depends on short–time wind variations. These results could be used to enhance the performance of operational models like STREET (Johnson et al., 1973) and OSPM (Hertel and Berkowicz, 1989), both of which assume that mass transfer velocity is proportional to a characteristic velocity in the ABL.

2. Methodology

2.1. Computational domain and boundary conditions

2D RANS and URANS CFD simulations were carried out with the commercial flow solver FLUENT widely used in industry and applied research. The computational domain, mesh and boundary conditions are shown in supporting material. An ideal 2D street canyon with dimensions H=18 m and W=6 m (AR=3) was considered. The inflow and outflow length and the vertical size of the domain were set to ensure that the turbulent flow was fully developed at the leading edge of the street canyon.

The computational mesh was a structured mesh comprising 256×256 quadrilateral cells inside the street canyon zone while upstream, downstream and along direction Y it numbered 256 quadrilateral cells. Wall y^+ is reported in Figure S1b in the SM, in the case of steady state simulation: it is always <1, which is the main mesh requirement to avoid the use of wall functions and to achieve an accurate prediction of the boundary layer also in the case of separated flows.

An LES simulation was also performed. In order to reproduce one of the 2D cases studied, periodic boundary conditions were applied to the side faces of the 3D domain required for the LES calculation. The other boundary conditions are the same as those described above. LES computational mesh was obtained by a refinement of the RANS mesh in the *X–Y* plane. The resulting grid resolution is twice the RANS mesh size and wall y^+ is much less than unit assuring an accurate prediction of near wall flow. The spanwise grid resolution was optimized by a grid convergence analysis. The adopted numerical schemes are second order accurate in space and time while the subgrid stress model is the classical Smagorinsky–Lilly model.

2.2. Simulations

The incompressible formulation of the RANS–URANS equations was used with species transport (air–CO mixture), neglecting chemical reactions and thermal effects. We adopted second–order central schemes in space and time and a *k–ω* SST turbulence model.

Preliminarily, steady state simulations were performed with constant inflow wind at 4 m s^{-1} and CO molar concentration of $3.72{\times}10^{-4}$ mol m^{-3} (equal to the 10^{-2} g m^{-3} limit value in European countries). The inlet turbulence intensity was set to 25% while the inlet turbulent viscosity ratio was set to 10 and wall roughness to $8{\times}10^{-2}$ m as in a previous study (Murena et al., 2011). Fluid was air with sea level constant properties.

The fully developed flow field obtained by steady state simulations was used as the initial flow field of the unsteady simulations. Unsteady (or wash–out) simulations were performed imposing a zero molar concentration of CO at the inflow boundary (for more details see Murena et al., 2011). In this way the initial uniform concentration of CO present in the calculation domain (CO=372 μmol m^{-3}) changes with time and space due to the washing out of CO from the computational domain and particularly from the street canyon cavity. Inflow wind was assumed both constant with time (v=4 m s^{-1}) and time–dependent. In the latter case it was described by sinusoidal functions or by real world data. To check the effect of short–time wind magnitude variations, sinusoidal functions have constant average velocity (v=4 m s^{-1}) and amplitude (±2 m s^{-1}) while time period ranges between 1 s and 40 s. Real world data were obtained using 50–Hz time resolution wind data measured at roof top level (45 m above street level) in Via Nardones, Naples (Spano, 2011). Data were time–averaged (0.1 s; 1 s and 10 s) before being used as inflow wind in simulations.

The aim of unsteady simulations is to evaluate the mass exchange rate between the canyon and the ABL. For this reason the time required to obtain a reduction of 50% (t_{50}) and 75% (t_{75}) of initial CO concentration = 372 μmol m^{-3} was calculated in two different volumes: (i) the whole street canyon volume; (ii) the "monitoring volume" defined as the space between 2 m and 4 m from the street level, where air is sampled and then analyzed by instruments in monitoring stations.

It is worth pointing out that, strictly speaking, the time scale of external forcing (i.e. wind variations) should be much greater than the time scale of turbulent fluctuations to assure a sufficient statistical sample for time averaging in the URANS equations (see for instance Pope, 2000). That said, it is usually sufficient that a distinct boundary between the two time scales exists. It has been verified that the case of real wind inflow with 0.1 s time average may be critical so that, in this case, an LES simulation has been also performed and compared with URANS. The time required for flow initialization to reach steady state in the LES simulation is about 400 s. Although not discussed, all proposed calculations are fully converged in time and while reducing mesh size.

3. Results and Discussion

3.1. Steady state simulations

Steady state simulations with constant wind velocity (v=4 m s^{-1}) entering the calculation domain (see the SM, Figure S1) and uniform CO concentration (CO=372 μmol m^{-3}) were preliminarily performed. The skin friction coefficient over the inflow and outflow walls is plotted and compared with an analytical rough flat plate solution (White, 1991), showing that the near field flow is correctly predicted, while the non–dimensional velocity profiles, at a station located 50 m upstream of the leading edge of street canyon, and the turbulent viscosity distribution show that the turbulence is fully developed and correctly predicted (see the figures in the SM).

The mean x–velocity profiles and turbulence intensity inside the street canyon obtained are shown respectively in Figure 1a and 1b, while the flow field inside the street canyon is shown in Figure 2. Both Figures 1 and 2 show the presence of two vortices as reported in numerous previous studies in the case of *H*/*W*=3 (e.g. Sini et al., 1996; Jeong and Andrews, 2002). Three smaller vortices are also formed in the bottom angles and in the top left angle of the street canyon (Figure 2).

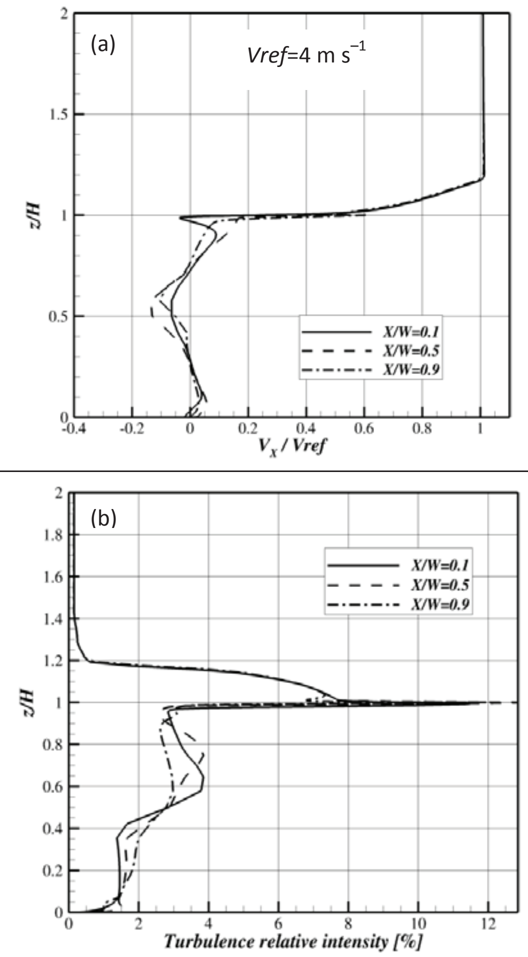

***Figure 1. (a)** Steady state solution: Computed normalized mean x–velocity profiles inside the street canyon, **(b)** Steady state solution: Computed turbulence intensity inside the street canyon.*

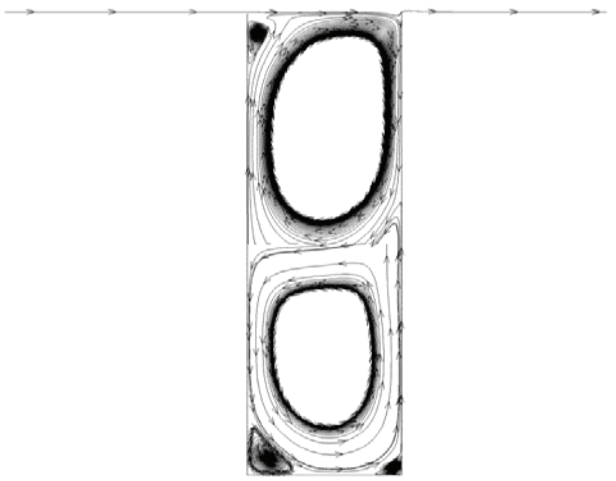

Figure 2. *Steady state solution: Flow field inside the street canyon.*

3.2. Unsteady simulations

Mass exchange. The rate of reduction of the spatially averaged CO concentration in the street canyon was evaluated adopting the same procedure reported in Murena et al. (2011). The spatially averaged concentration of CO was evaluated in the whole street canyon volume and in the volume between *H*=2 m to *H*=4 m from the street level. The height of 2–4 m is the typical air sampling height used at air quality monitoring stations. In the following it will be indicated as the "monitoring volume". Curves of CO concentration in the monitoring volume and total volume vs. time are reported in Figure 3. Curves are parametric with the time period of inflow wind function.

It can be observed that increasing the frequency of inflow wind increases the rate of reduction of CO in the monitoring volume. This is proof of the better efficiency of mass transfer with wind frequency: the CO reduction rate peaks at the period *T*=1 s and diminishes as the period increases from *T*=2.5 s to *T*=40 s. The minimum CO reduction rate is observed when the inflow wind has constant velocity (i.e.; $T \rightarrow \infty$). The effect of the time period is not linear: the reduction rate of the CO concentration increases sharply from *T*=5 s to *T*=2.5 s and *T*=1 s. Minor changes are observed when T changes from ∞ to 5 s. Similar behavior is also observed if all the canyon volume is considered (Figure 3b). In this case the CO reduction rate is very fast at the beginning, due to the wash–out of CO from the upper side of the canyon, and less time is required to reach a fixed percentage of CO reduction with respect to the "monitoring volume".

The CO reduction rate can be quantified by making reference to the time required to reach 50% (t_{50}) or 75% (t_{75}) of wash–out of the initial CO concentration. Table 1 shows that t_{50} reduces from >3 000 s if the inflow wind is constant to 678 s if the time period is *T*=1 s.

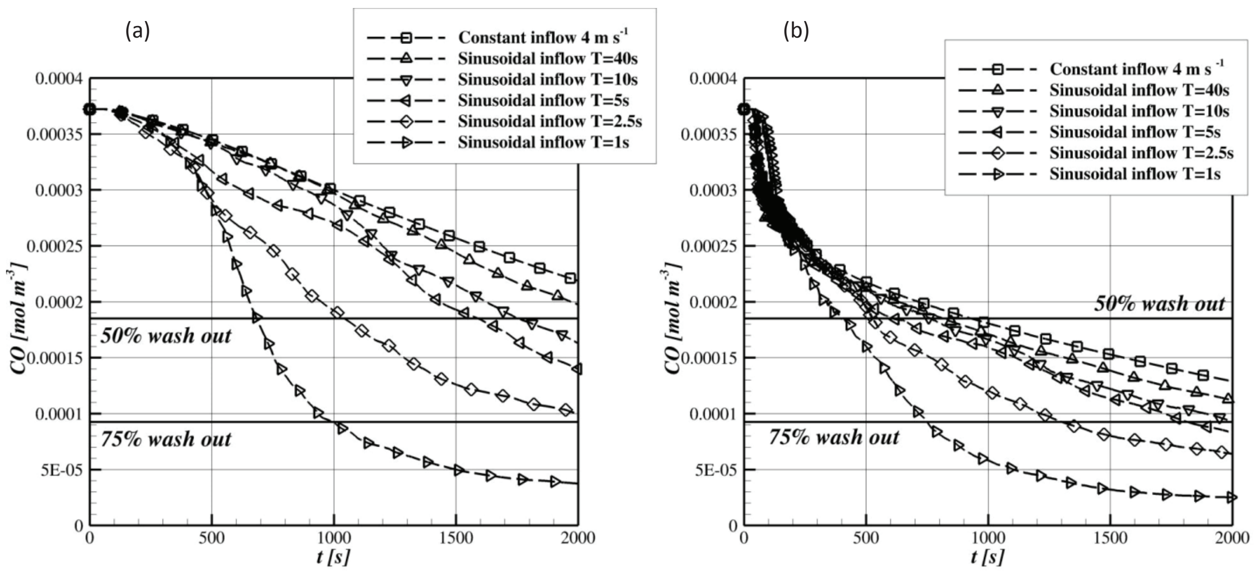

Figure 3. *Results of wash–out CFD simulations: Average CO concentration vs. flow time at different wind speed oscillation periods.* ***(a)*** *monitoring volume;* ***(b)*** *whole street canyon.*

Table 1. *Time occurring for 50% (t_{50}) and 75% (t_{75}) reduction of initial CO concentration in the "monitoring volume" (H=2–4 m) as a function of period (sinusoidal function) and in the case of time averaged real world data*

Inflow Wind	Period (s)	Averaging Time (s)	t_{50} (s)	t_{75} (s)
Sinusoidal function	1		678	1 000
	2.5		1 047	2 050
	5		1 570	2 500
	10		1 800	2 900
	40		2 500	>3 000
	∞		>3 000	>3 000
Sonic data		0.1	1 100	2 000
		1	1 800	2 850
		10	2 100	>3 000

To better consider real cases, 50–Hz resolution wind data measured at roof top level (45 m above street level) in Via Nardones, Naples (Spano, 2011), were processed to obtain 0.1 s; 1 s and 10 s averaged data (Figure 4). The time–averaged magnitude velocity was 4 m s^{-1} in order to compare the results obtained with those with sinusoidal functions for inflow wind. The results of CFD simulations using with real world data are also reported in Figure 5 and Table 1.

In Figure 6 in the support materials the CO reduction rate obtained by an LES simulation, in the case of 0.1 s average, is proposed and compared with the URANS result. Significantly, the URANS result is in satisfactory agreement with the LES prediction.

Figure 5 shows a dependence of mass transfer rate on the averaging time interval. When the averaging time is 0.1 s, simulation results are very close to those obtained assuming a sinusoidal function with *T*=2.5 s. The curve obtained with a 1 s averaging time is well fitted by simulation with a sinusoidal function of time period *T*=10 s. By contrast, when the averaging time of sonic data is 10 s the corresponding curve fits that obtained with constant inflow wind. The same correspondence holds true for washing–out time (Table 1). The lower is the averaging time interval the higher is the mass transfer rate and hence the lower is the values of t_{50} and t_{75}.

This result is of great practical interest because it means that short–time wind variations in the real world have a frequency that can significantly affect mass transfer between the canyon and the ABL. To consider this effect it is necessary to have a high frequency measure of wind intensity.

This result is apparently in contrast with the findings of Xie (2011) who observed it was enough to adopt 30 s or 60 s time–averaged real world data to obtain a significant improvement in performance of CFD simulations. This discrepancy may derive from some differences between our study and that of Xie (2011), whose calculation domain was a complex 3D real case (Marylebone Road) where wind direction variations played a major role. Moreover, the study in question concerned a short time emission (15 min). In particular, the absence of the effect of wind direction variations in our study (the geometry being bidimensional), can justify the need to use a shorter averaging time, with respect to Xie (2011), to observe a significant effect on simulation results.

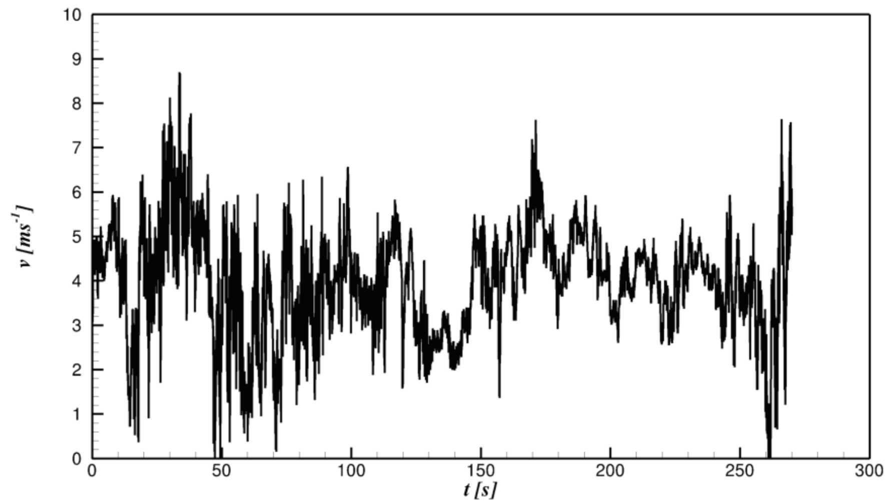

Figure 4. *Time–averaged horizontal wind component magnitude measured in Via Nardones in Naples (data from Spano, 2011).*

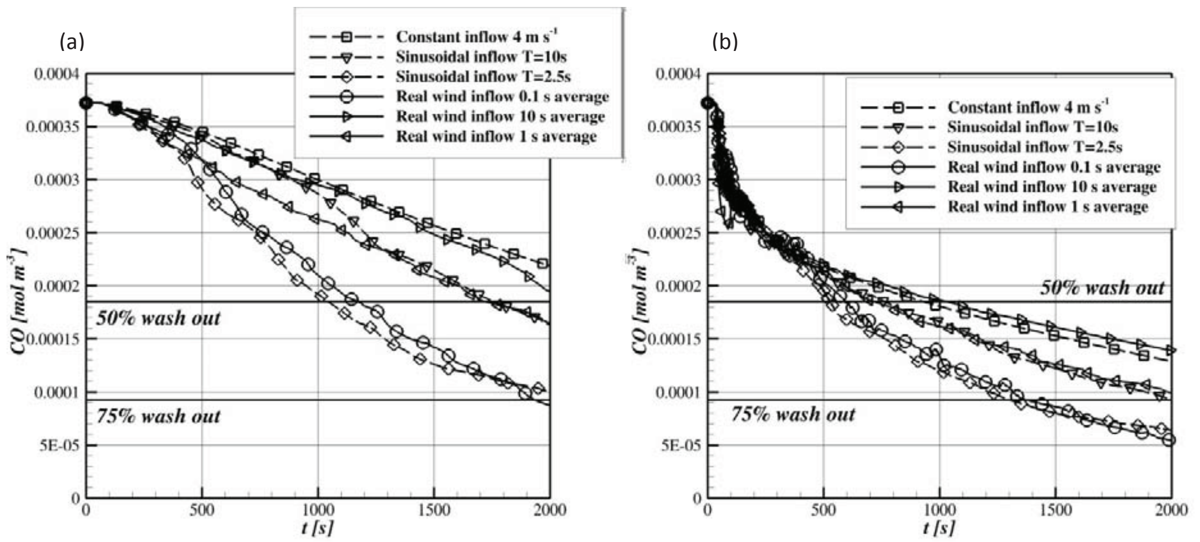

Figure 5. *Comparison of CO wash–out CFD simulations with real wind inflow conditions and sinusoidal function.* ***(a)*** *monitoring volume;* ***(b)*** *whole street canyon.*

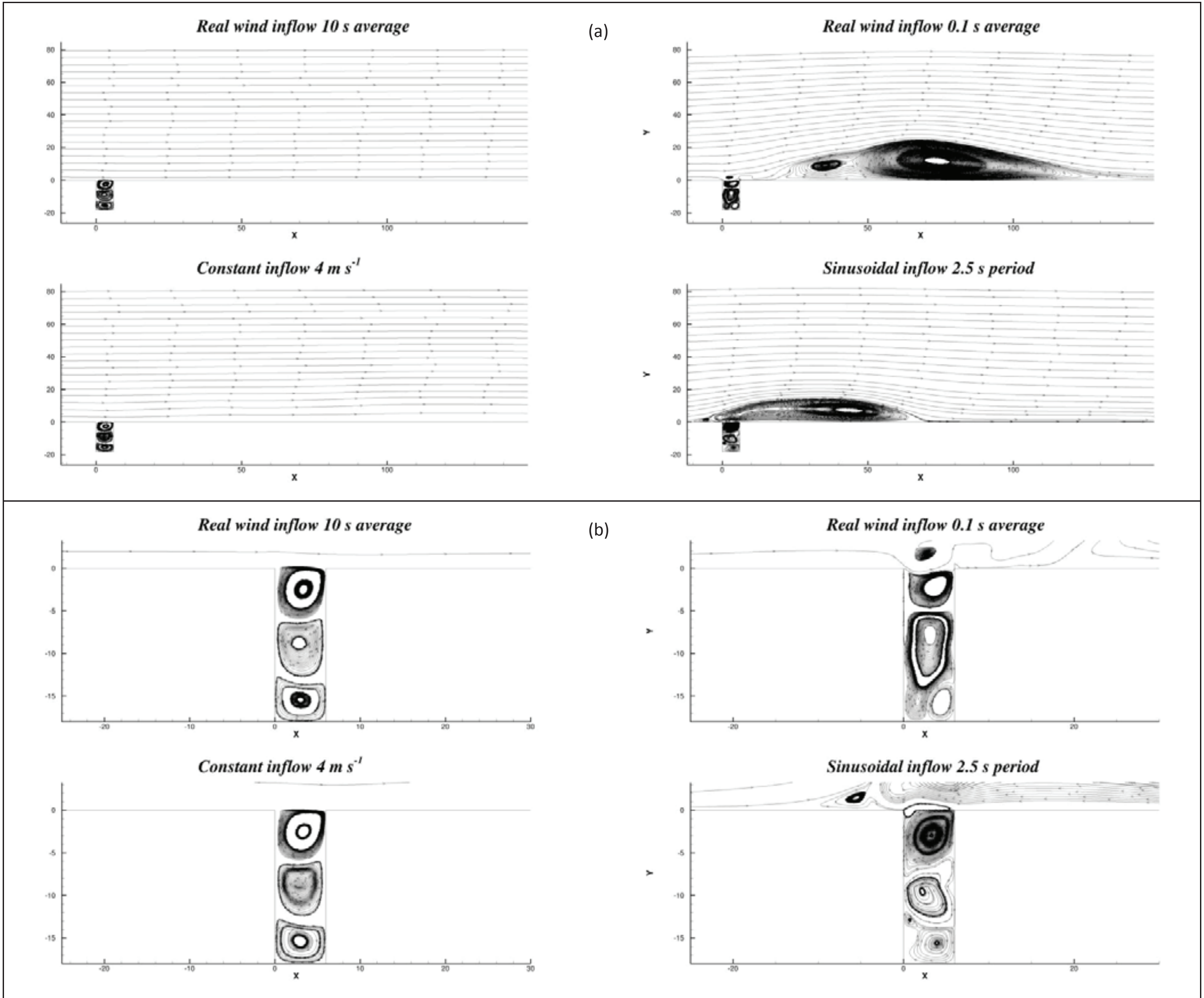

***Figure 6. (a)** Vortical structures above the street canyon deriving from unsteady flow field at 1 000 seconds; **(b)** Vortical structures in the street canyon deriving from unsteady flow field at 1 000 seconds.*

To explain the increment of mass transfer due to time–dependent inflow wind magnitude, Figures 6a and 6b are reported as exemplary snapshots of the instantaneous flow field. Significantly, the flow field obtained with constant inflow is very similar to that obtained with real world data averaged on a time interval of 10 s (Figure 6a, left). In both cases vorticity is at a minimum in the ABL above the roof top level. When shorter–time wind variations (T=2.5 s in the case of a sinusoidal function or averaging time = 0.1 s in the case of real world data) a considerable vorticity over the roof top level above and downwind of the cavity is observed (Figure 6a, right). The presence of significant turbulent structures induces a greater mass exchange between the street canyon and the ABL. Analogously (Figure 6b), a major vorticity is observed in the street canyon when inflow wind assumes a higher frequency.

It must be stressed that the results obtained also depend on the absolute values of constant inlet parameters adopted: average velocity (4 m s^{-1}) and amplitude (±2 m s^{-1}). If these parameters are changed, t_{50} and t_{75} values will consequently change as well.

It is known (Sini et al., 1996; Salizzoni et al., 2009; Murena et al., 2011) that inflow wind average velocity increases the mass transfer rate. The effect of amplitude was studied by assuming an average velocity of 4 m s^{-1} and amplitude of 1–2–4 m s^{-1}. The wash–out curves obtained show that upon increasing the amplitude the washing–out time decreases (Esposito and Boffardi, 2012).

4. Conclusions

2D URANS CFD simulations conducted on a street canyon with an H/W aspect ratio of 3 showed that short–time variations of wind magnitude can significantly influence the mass transfer between the street canyon and the atmospheric boundary layer. Mass transfer rate was evaluated by performing wash–out simulations of the street canyon filled with a mixture of air/CO while the inflow wind was CO–free air. The spatially averaged CO concentration in the street canyon was evaluated at different times and concentration vs. time curves were obtained.

As the time dependence of short–time wind variations is chaotic, such variations cannot be represented exactly by an analytical function. We assumed a sinusoidal function with average velocity (4 m s^{-1}) and amplitude (±2 m s^{-1}) to describe the time dependence of wind magnitude with time. Varying the time period of the sinusoidal function in the range 1 to 40 s, it was observed that the mass transfer rate decreased as the time period increased.

The time required to reduce the CO concentration in the "monitoring volume" (the volume between 2 and 4 m from the street level) to 50% of the initial value (t_{50}) reduces from more than 3 000 s obtained with time constant inflow wind to t_{50}=678 s, corresponding to inflow wind simulated by a sinusoidal function with a period *T*=1 s.

If inflow wind is simulated using real world data, measured by a sonic anemometer, t_{50}=1 100 s when sonic data are averaged on a time interval of 0.1 s. This result is very similar to that obtained assuming a sinusoidal function with *T*=2.5 s (t_{50}=1 047 s). If a higher averaging time is used, t_{50} increases. With an averaging time of 10 s the results are very similar to those obtained with a constant wind inflow.

Comparison with an LES simulation performed in the case of 0.1 s time averaged real world data showed that the URANS prediction is in satisfactory agreement.

Hourly average values of wind magnitude and direction are normally adopted to simulate real world cases in CFD studies. The results of this paper show that this practice can underestimate the mass transfer rate between the street canyon (or urban canopy) and atmospheric boundary layer. As a consequence, pollutant concentrations at street level can be overestimated. These findings obtained with 2D simulations have to be confirmed by 3D simulations.

The results are of interest both to gain insights into the mass transfer mechanism between urban canopies and the ABL and to enhance the performance of local scale models for the simulation of air quality in urban areas.

Supporting Material Available

Computational mesh, domain and boundary conditions (Figure S1a), Wall y^+ vs. Re_X (Figure S1b), Computational mesh in the street canyon (Figure S2), Steady state solution: computed skin friction coefficient vs. Re_X compared to analytical solution (Figure S3a), Steady state solution: computed non–dimensional velocity profile vs. y^+ compared to log law for rough walls (Figure S3b), Steady state solution: contour of turbulent viscosity (Figure S4), Horizontal wind velocity component measured by ultrasonic anemometer in Naples (Figure S5), Comparison between LES and URANS predictions in wash–out simulations (Figure S6). This information is available free of charge via the Internet at http://www.atmospolres.com.

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