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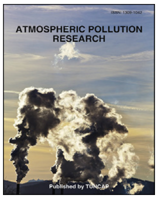

Original article

Effect of balconies on air quality in deep street canyons

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ABSTRACT

This study discusses the effect of balconies on the dispersion of vehicular pollutants inside a deep street canyon and on the mass transfer rate between the canyon and the above atmosphere. 3D computational fluid dynamics (CFD) simulations were performed considering the presence of balconies of different dimensions in a deep street canyon with aspect ratio H/W = 3. The effect of two geometrical parameters has been investigated: the balcony depth and the horizontal distance between two balconies, the other geometrical parameters remaining constant. CFD simulations have been carried out adopting the scale adaptive simulation (SAS) model. Results show that the presence of balconies can determine a significant modification in the flow field inside the street canyon with a less homogeneous dispersion of pollutants emitted by vehicles circulating in the street and a less effective mass exchange with the above atmosphere. At the present models developed to assess pollutant concentration levels in street canyons do not consider the presence of balconies. As consequence, an underestimation of real concentration levels could occur. Therefore, results obtained can give a contribution in the development of more feasible air pollution models in urban areas at local scale, and useful information for design of building facades that minimize the entrapping of vehicular pollutants at pedestrian level in street canyons.

1. Introduction

The development of models to predict accurate evaluation of pollutant concentration at street level in urban areas is hindered by the complexity of urban areas, the differences between each other and the difficulty in modelling traffic flows and on-road vehicular emissions. Moreover, even though the technology in the treatment of vehicular exhaust has drastically reduced the emission factors of new vehicles, atmospheric pollution in urban areas is still an issue in many cities all over the world.

Pollutant dispersion in urban areas is determined by several phenomena at different scales: from regional (≈100 km) to local (≈1 m). Local scale is typically referred to a single road named as “street canyon”. The solution of problems at local scale can be achieved by numerical modelling using CFD (Computational Fluid Dynamics). Its application is however limited by high computational costs. Moreover, CFD simulations can be operated only by highly qualified personnel. The alternative to numerical models is represented by “operational models” (Vardoulakis et al., 2003). Operational models can be used also by non-specialist users and can treat a large variety of situations with limited computing resources (Soulhac et al., 2013).

In the most of cases operational models are “box models” including as many mass balances equations as the number of boxes defined in the street canyon (Murena et al., 2011). Homogeneous concentration and steady state conditions are generally assumed in each box. The assessment of hourly averaged time values of pollutants concentration in the street canyon is the final goal of these models.

Operational models developed for a single road can be the basis of models for application in urban areas as: ADMS-URBAN (McHugh et al., 1997) and SIRANE (Soulhac et al., 2011).

In the case of an urban area, or a district, each street is involved in several mass transfers: i) with the above atmosphere; ii) along the street (Soulhac et al., 2008); iii) with other streets at intersections (Soulhac et al., 2009). This paper deals with the mass transfer between the street and the above atmosphere.

The mass transfer between the canyon and the atmospheric boundary layer (ABL) has been studied by several authors. A rather

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incomplete list includes: Sini et al. (1996), Bentham and Britter (2003), Barlow et al. (2004), Hamlyn and Britter (2005), Salizzoni et al. (2009), Murena et al. (2011), Chung and Liu (2013).

The mass exchange between 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). It is widely assumed that the instantaneous (turbulent) contribution to mass transfer velocity is higher than the mean (advective) contribution. However, the latter can be significant when the building height is not uniform (Hamlyn and Britter, 2005) or the wind has a component parallel to the street axis (Yaghoobian et al., 2014). Salizzoni et al. (2009) observed that mass transfer is entirely governed by the fluctuating component of the turbulent flow. Murena and Mele (2014) observed a significant influence of short-time variations of wind velocity on mass transfer rate.

In a box-model approach the mass transfer rate between the street and the atmosphere is expressed through the definition of a spatially averaged mass transfer velocity u: $Q = uWL(C_{street} - C_{ext})$ where Q is the emission rate of the pollutant in the street [g s^{-1}]; W and L are the canyon width and length respectively; $(C_{street} - C_{ext})$ is the difference in pollutant concentration between the canyon and the atmosphere (hourly average values); and u represents the velocity of the mass transfer [m s^{-1}]. In the case of deep street canyons (H/W > 1.6–2) it would be more appropriate to use a multi-box model (Murena et al., 2011), because of the formation of two or more counter-rotating vortices. However, also in this case, the mass balance equation can be written as before defining an overall mass transfer velocity (Murena et al., 2011) to quantify the overall mass transfer process from the bottom volume of the canyon to the ABL.

For a large application of operational models, it is mandatory to obtain precise evaluation of mass transfer rate between street canyon and ABL from commonly available meteorological and geometrical data. In many cases mass transfer rate has been evaluated using a reference velocity. In the OSPM model (Berkowicz et al., 1997), when H/W ≥ 1, the concentration of pollutant in the street canyon is evaluated as: $c = \frac{Q}{W\sigma_{wt}}$ where σ_{wt} is the canyon ventilation velocity $\approx 0.1u_w$ where u_w is wind speed at the top of the canyon. Soulhac et al. (2013) examined the parametric relations needed to estimate spatially averaged pollutant concentration in street canyons with a box model approach. They found a good agreement between model and wind tunnel data when the wind direction was >45° with the road axis, showing the skills of this approach in modelling pollutant dispersion in urban areas. In their model the mass transfer velocity is proportional to friction velocity (u_*) and concentration of pollutant in the street canyon is $c = \frac{Q}{W}\frac{\pi\sqrt{2}}{u_*}$. Their result is analogous to that obtained by Berkowicz et al. (1997) and by Hotchkiss and Harlow (1973). These results may be applied to a single ideal street canyon. If an urban street canopy, more similar to real conditions, is considered some modifications take place. Applying the box model approach for the interpretation of wind tunnel data of a urban canopy realized by an array of square buildings with H/W = 1 and L = 5H, Soulhac et al. (2013) observed that better results are obtained if the box model equation is modified as $c = \frac{Q+Q_{up}}{u_w WH + u_d WL}$ where Q_{up} is the mass flux entering in the canyon from the upwind intersection and L is the street length.

It must be observed that results above reported make reference to idealised street canyons where buildings are represented as parallelepipeds. In some cases, but not always, an equivalent roughness is imposed at building facades (Vernay et al., 2014). In wind tunnel experiments low roughness surface are often adopted for a more accurate near wall modelling with CFD (Allegrini et al., 2013) but this does not always correspond to real cases.

The real building facades geometry, and particularly the presence of balconies, can have an effect: i) on the flow field inside the street canyon as shown in studies focused on the wind induced ventilation (Mohamed et al., 2009); ii) on the external noise (Lee et al., 2007); iii) on the heat exchange (Lignarolo et al., 2011). It is logical to guess an effect also on mass transfer rate inside the canyon and with the above ABL. As a matter of fact, studies considering the presence of trees inside the street canyon (Gromke et al., 2008; Buccolieri et al., 2009) showed an effect on the flow field.

Therefore, a more realistic representation of building facades could be necessary as reported by Soulhac et al. (2013) in their conclusions.

The aim of this study is to verify the effect of real building facades geometry on flow field inside the deep street canyon and on mass transfer rate between the canyon and the above ABL. In particular, the presence of balconies has been studied.

The analysis has been carried out by performing 3D CFD simulations with periodic boundaries adopting the recently proposed scale adaptive simulation (SAS) model of Menter and Egorov (2010). The SAS model can be ascribed to the category of hybrid models such as DES (detached eddy simulation) by Spalart et al. (1997), Spalart (2000), however SAS model has been proved to have a less sensitivity to grid spacing (Egorov et al., 2010).

Depth of balconies and balcony to balcony distance were varied to verify their effect on flow field inside the canyon and on mass transfer rate.

Due to the few availability of experimental data, validation was performed comparing results with an LES simulations. CFD modelling has shown in other different studies to fit quite well the observations from wind tunnel data (Santiago and Martin, 2008) or real world data (Santiago et al., 2010, 2013).

The results obtained give a contribution for a better evaluation of the mass transfer rate between a deep street canyon and the atmosphere which is a key parameter in the development of operational models.

2. Methodology

The procedure adopted to perform the simulations is analogous to that of previous papers (Murena et al., 2011; Murena and Mele, 2014) but with some differences that will be highlighted.

The computational domain is reported in Fig. 1 with a zooming on the canyon with balconies. Boundary conditions applied for all simulations are also reported in Fig. 1. It is a 3D model with periodic boundaries that are represented by dashed lines in the front view picture of the street canyon in Fig. 2. We have adopted this model also for those cases that could be studied as 2D geometry: e.g.; absence of balconies ($L_b = 0$) or continuous balconies ($\Delta_b = 0$).

The geometrical description of the street canyon is reported in Fig. 2. In all simulations the aspect ratio, the ratio between building height H and street width W, was H/W = 3 with H = 18 m and W = 6 m. Following the usual classification of street canyons (Oke, 1987) this is a deep street canyon.

The dimension of balconies is defined by the following geometrical parameters: balcony depth (L_b); balcony width (W_b), balcony height (h_b); vertical distance between two balconies (H_b) and horizontal distance between two balconies (Δ_b).

Some geometrical parameters were kept constant in all simulations: $W_b = 1.5$ m, $h_b = 1$ m; and $H_b = 3.5$ m. These values are typical of buildings in the historical centre of Naples characterized by two typologies of streets: the principal roads have H ≈ 30 m and W = 20–30 m. The secondary streets have W = 6–7 m and H = 18–30 m. Dimension of balconies are: depth 0.5–1 m; length 1–2 m; and horizontal distance between two balconies from 1 to 3 m.

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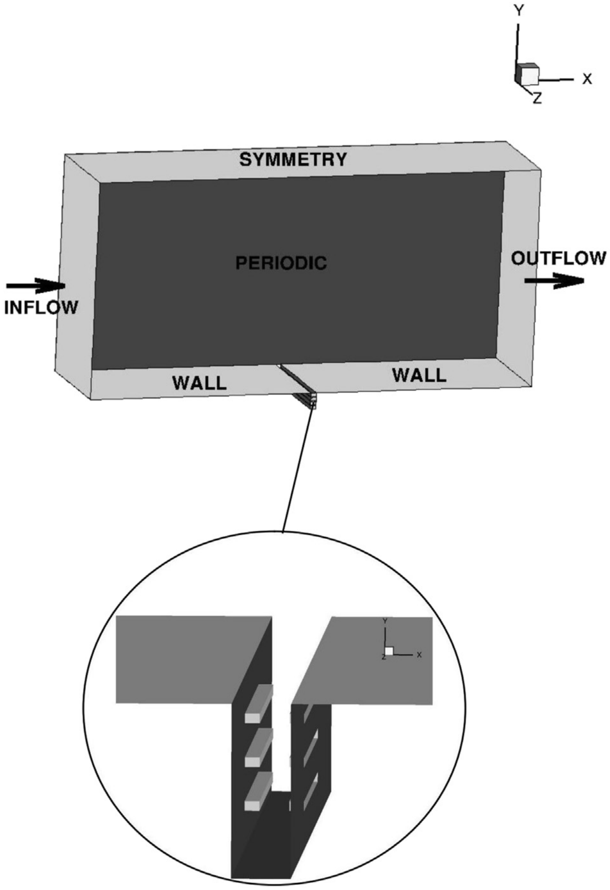

Fig. 1. Computational domain and boundary conditions.

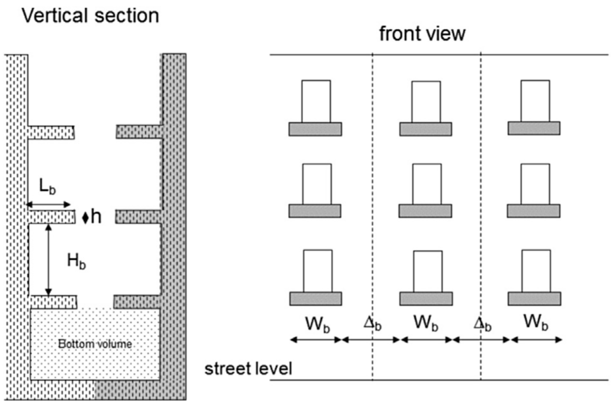

Fig. 2. Geometrical description of the street canyon (not in scale).

The remaining two parameters: balcony depth (L_b) and horizontal distance between two balconies (Δ_b) were varied to study their effect (Table 1) on the flow field inside the canyon and on the mass transfer with above atmosphere. When the horizontal distance $\Delta_b = 0$ it corresponds to a continuous balcony. When the depth $L_b = 0$ or $\Delta_b \to \infty$ it corresponds to the absence of balconies.

Table 1
Range of values of geometrical parameters of balconies investigated [m].

L_b	W_b	h_b	H_b	Δ_b
0–1.5	1.5	1	3.5	0–2.5

The computational grids employed for the different cases studied are structured with quadrilateral cells and respect all quality requirements for turbulent flows, in particular in terms of y$^+$. In Fig. 3 it is shown that y$^+$ is always <1 that is the main mesh requirement to achieve an accurate prediction of the boundary layer also in case of separated flows.

The unsteady incompressible formulation of the Navier–Stokes equations was used with species transport (air–CO mixture), neglecting chemical reactions and thermal effects. All simulations were performed employing the SAS (Menter and Egorov, 2010) model adopting second-order central schemes in space and time.

Background, derivation and basic equations of the model are widely detailed in Menter and Egorov (2010). Such as discussed by the authors, a very interesting feature of the SAS concept is that a variation of solutions from an LES type to URANS type is achieved depending on the time step size, allowing for a fall back to URANS solution if the space and time resolution is not sufficient for resolving the turbulent scales. Such feature is essential when a LES grid and a LES time step cannot be maintained in the whole computational domain (this happens in many situations), in fact LES or DES models can return wrong results and strong numerical instabilities when a too coarse grid or a too large time step is adopted, while SAS methods is able to obtain correct results also in this cases. The SAS model of Menter and Egorov has been validated in Egorov et al. (2010) by performing several unsteady simulations of complex flows and comparing the results with LES and DES results.

Conditions at inlet (INFLOW in Fig. 1) are: inlet velocity = 4 m/s; inlet turbulence intensity and turbulent viscosity ratio equal respectively to 25% and 10. Fluid was air with sea level constant properties.

Analogously to previous papers, we have preliminarily performed steady state simulations with the aim to obtain the flow field inside the canyon. In steady state simulations inlet and initial CO molar concentration were set to 372 μmol m^{-3} ($\approx$10 mg/m^3). A developed flow field (mean steady state) inside the canyon was reached in about 1000 s of physical time.

Unsteady state (wash-out) simulations were performed to obtain information on the rate of mass transfer process (Murena et al., 2011; Murena and Mele, 2014) starting from the developed flow field obtained by steady state simulations. Inlet conditions were the same of steady state simulations apart from CO concentration that for $t > 0$ was set $= 0$ (i.e.; CO-free air enters the calculation domain). As a consequence, CO concentration in the

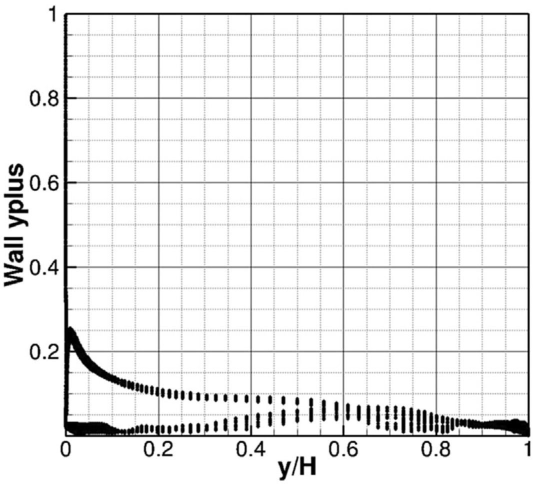

Fig. 3. y+ distribution inside the street canyon (absence of balconies case).

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street canyon reduces with time at a rate depending from the mass transfer velocity between the canyon and the above atmosphere.

In all unsteady simulations CO spatially averaged concentration was evaluated as function of time both in the total street canyon volume and in the bottom volume defined as the volume from street level to the height of the first level balcony equal to 3.5 m (Fig. 2).

We have performed preliminary convergence studies reducing time step and mesh size and increasing the computational domain. As an example, the optimal mesh size in the case of absence of balconies counts about 2 million cells. The results of convergence study are reported in Fig. 4 where the wash out curves computed at different Courant numbers (CFL) are reported in the case of absence of balconies, the results are convergent while reducing the CFL and they are in good agreement with the curve obtained performing an LES simulation with CFL = 1 that is reported as validation of the model. The physical time step used in all unsteady simulations was set to obtain a CFL below 10.

3. Discussion and results

Results of steady-state CFD simulations give an insight on the effect of balconies on the flow field inside the canyon. In Fig. 5 streamlines in the mid plane of the canyon are plotted in the case of 1 m depth balconies with horizontal distance between balconies equal to: 0 m (up); 0.5 m (middle); 2 m (bottom).

The differences among the flow fields are clearly visible: in the case of continuous balconies (up) the vortex structures and recirculation zones inside each part of the canyon appear well distinct, differently in the case of non continuous balconies the streamlines are much more connected across the different parts of the canyon. It is worth noting that reducing the horizontal distance (0.5 m) between the balconies (middle) the vortex structures tends to become similar to the case of continuous balconies (up).

In Fig. 6 the three components of the mean velocity profiles along the mid line of the mid plane of the canyon are plotted for the three different cases previously discussed.

It is interesting to note the differences in the y and z components that show how the separated balconies cases induce stronger 3D flow fields with respect to the continuous balconies case. In particular, it is worth noting that the y and z components of mean velocity are negligible in the bottom volume of the street canyon in the case of continuous balconies. The analysis of Figs. 5 and 6 suggests that the vortex structures evidenced in Fig. 5 in the case of continuous balconies are essentially 2D.

The effect of balconies on the mass transfer rate between the canyon and the above atmosphere was assessed through “unsteady simulations” or “wash-out simulations” described in Methodology section. The procedure adopted was the same reported in previous papers (Murena et al., 2011; Murena and Mele, 2014). Curves of CO

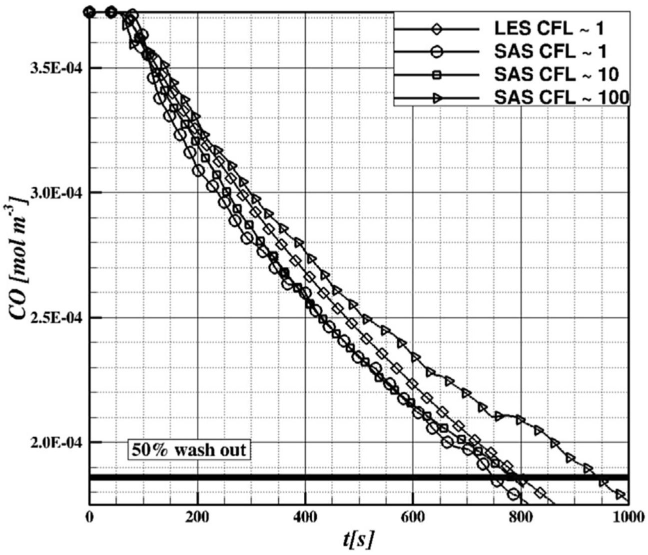

Fig. 4. Validation and grid sensitivity study. Spatially averaged concentration of CO in the bottom volume computed at different CFL numbers by SAS model and an LES simulation (absence of balconies case).

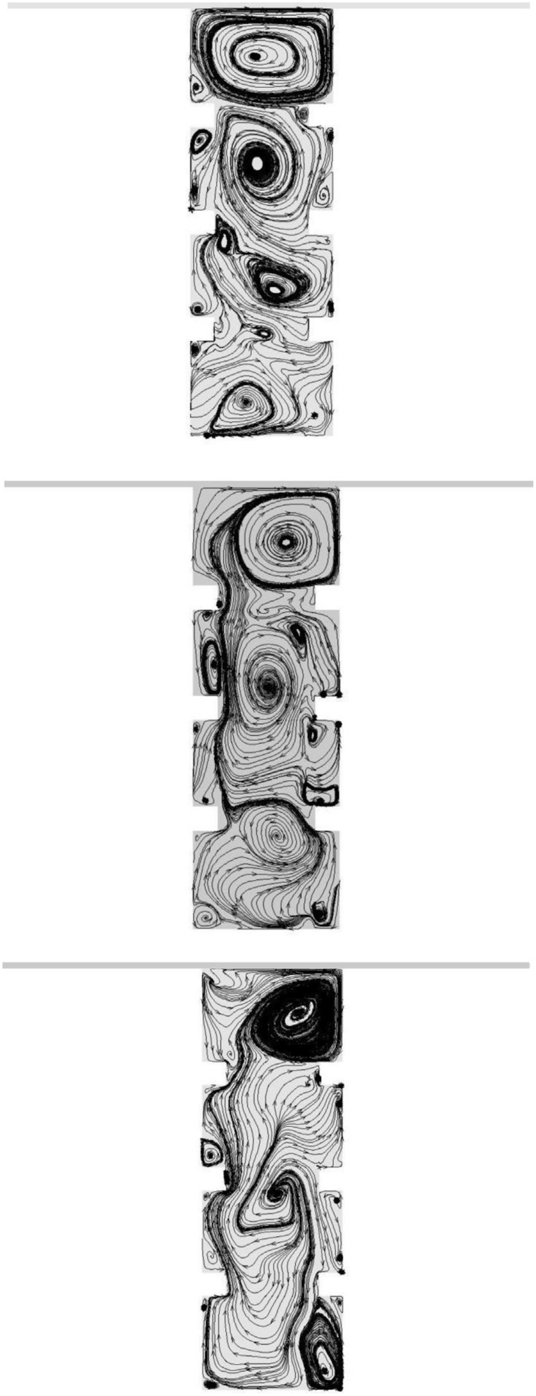

Fig. 5. Streamlines inside the street canyon (mid plane). Up: continuous balconies; middle: 0.5 m horizontal distance; bottom: 2 m horizontal distance. In all three cases the balcony depth = 1 m.

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spatially averaged concentration with time have been evaluated both in the total street canyon volume and in the bottom volume (Fig. 2). In this paper results obtained for the bottom volume will be mainly discussed. In fact, the evaluation of spatially averaged concentration of CO in the bottom volume is of particular interest for an assessment of the impact of balconies on air quality and, consequently, on human health because the air there contained is breathed by pedestrians and measured by eventually present air quality monitoring stations or analysers.

Results of wash-out curves are reported in Fig. 7. Top diagram shows the effect of balcony depth in the case of horizontal distance = 0 while bottom diagram the effect of horizontal distance between two balconies in the case depth = 1 m.

A delay time is observed before the CO concentration in the bottom volume starts reducing. The delay time is the result of two effects: i) the time necessary for the free CO air entering the dominium of calculus to wash the atmosphere above the canyon (Murena and Mele, 2014) that is about 60 s; ii) the delay time for

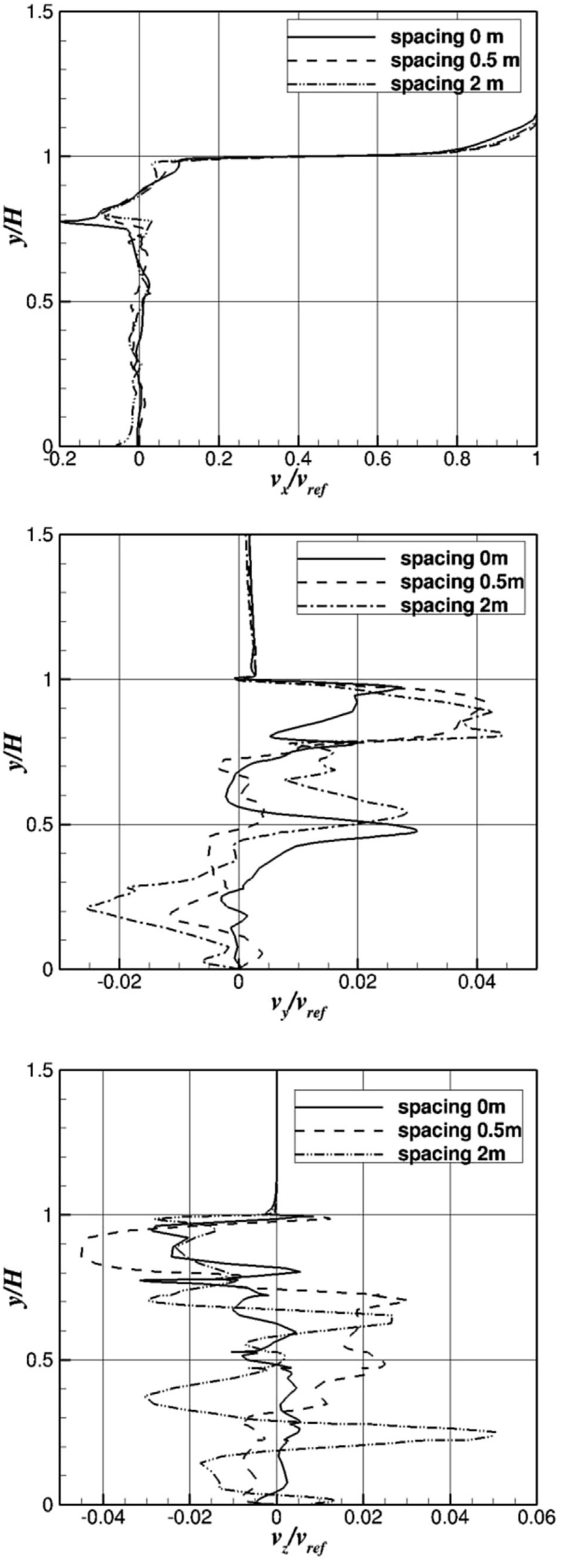

Fig. 6. Components of the mean velocity profiles inside the street canyon (mid line—mid plane). Up: X component; middle: y component; bottom: z component. In all three cases the balcony depth = 1 m.

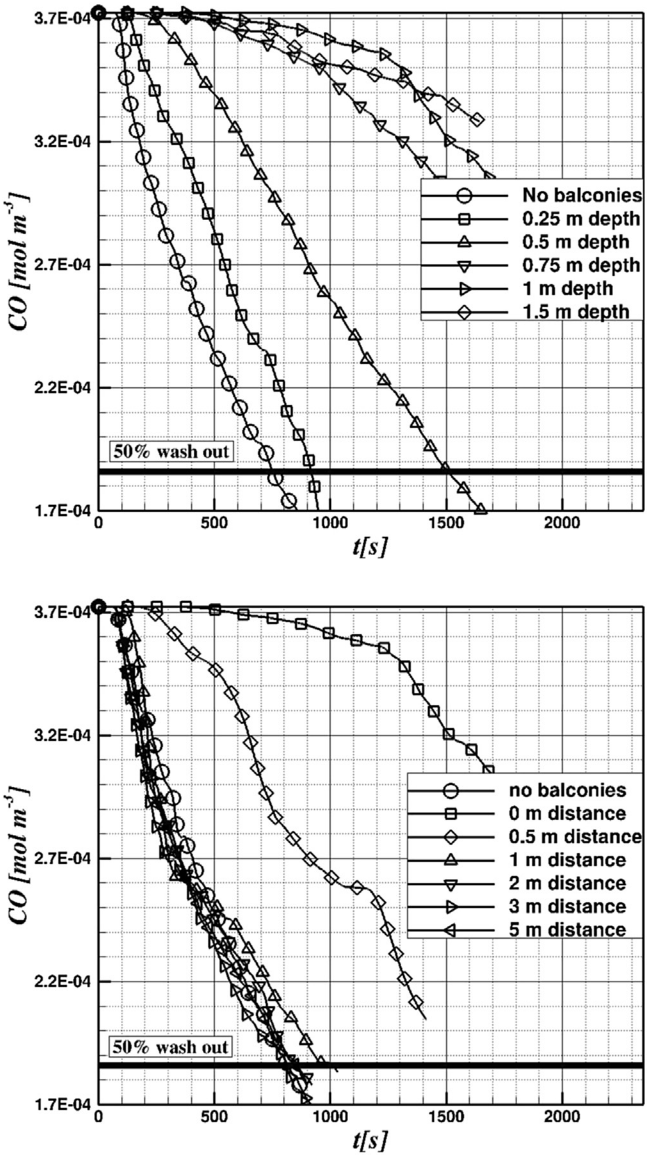

Fig. 7. Spatially averaged concentration of CO in the bottom volume with time in wash out simulations. Up: effect of balcony depth (horizontal distance = 0); bottom: effect of horizontal distance between balconies (balcony depth = 1 m).

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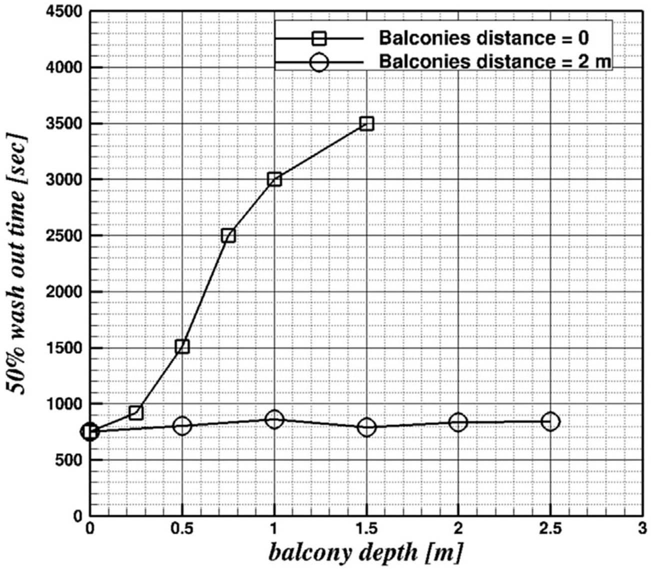

Fig. 8. Dependence of 50% wash-out time from balcony depth parametric with horizontal distance between two balconies.

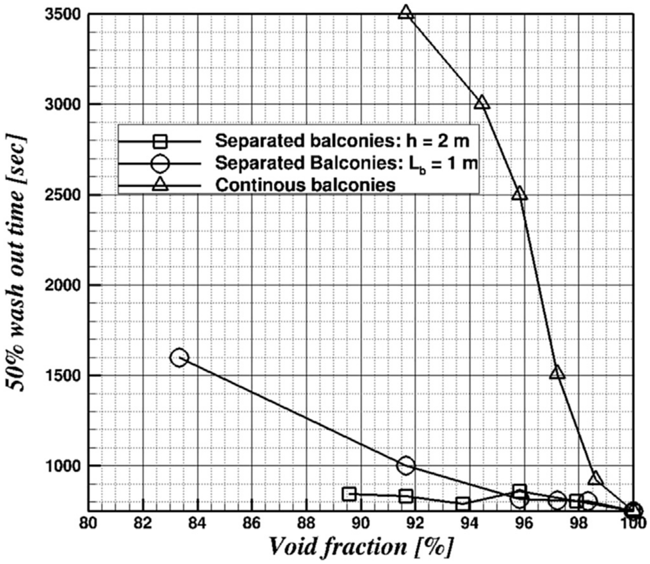

Fig. 10. Dependence of 50% wash-out time from void fraction.

starting the mass transfer of CO from the bottom to the upper volume. Curves reported in Fig. 7 shows generally an effect of the presence of balconies on the rate of the wash out process and consequently on the mass exchange between the bottom volume and the above atmosphere.

In the up diagram in Fig. 7 depth was varied from 0 m to 1.5 m. Depth = 0 m corresponds to the absence of balconies or flat facades. As expected the higher the balcony depth the slower the rate of wash-out. From 0 to 0.25 m the effect of balcony depth is less relevant while it becomes evident when the depth is equal or higher than 0.5 m.

Down diagram of Fig. 7 shows the effect of horizontal distance between balconies (Δ_b) in the range from 0 to 5 m. Curves reported correspond to simulations for a balcony depth $L_b = 1$ m. Results show that wash out rate increases strongly when horizontal distance is enhanced from 0 m to 1 m and after is quite constant and then independent from the horizontal distance.

To make a quantitative comparison of wash-out curves reported in Fig. 7, the time necessary to reach a 50% reduction of CO initial concentration (t_{50}) was evaluated for each of the simulations performed (Murena et al., 2011). Other authors (Chan et al., 2003) use as parameter to evaluate the effectiveness of mass transfer rate the retention value defined as the quantity of pollutant found inside the canyon over the total pollutant released in a specified time. In our simulations we do not consider the release of CO as vehicular pollutant. Therefore, retention value cannot be evaluated.

Fig. 8 shows the values of t_{50} in function of balcony depth parametric with the horizontal distance assuming $\Delta b = 0$ m and $\Delta b = 2$ m. It can be noted that, for $\Delta b = 0$ m (infinite length balcony or continuous balcony), the 50% wash out time is strongly influenced by the balcony depth. In fact t_{50} values are between $\approx$800 s, case with no balconies, and $\approx$3500 s when depth is 1.5 m. It must be remembered that the street width is 6 m. Therefore, theoretically maximum balcony depth could be $L_b = 3$ m to which it would correspond $t_{50} = \infty$. But it would be a non-realistic case.

Results are quite different for simulations with horizontal distance between balconies $\Delta b = 2$ m. In this case the effect of balcony

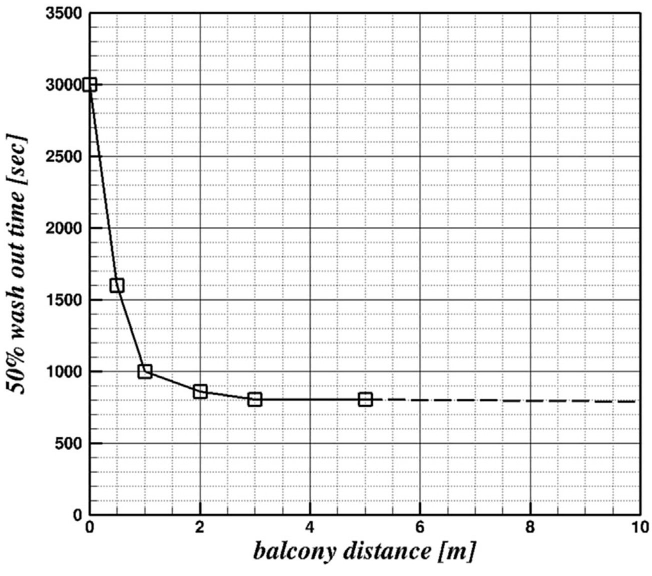

Fig. 9. Dependence of 50% wash-out time from the horizontal distance between balconies. Results are referred to a balcony depth of 1 m.

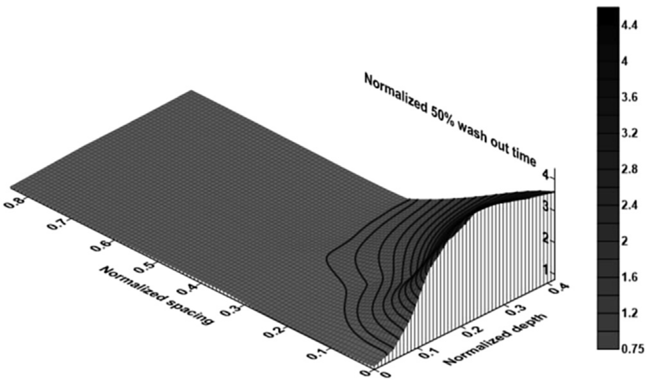

Fig. 11. Non dimensional t_{50} vs. non-dimensional depth (L_b/W) and non-dimensional horizontal distance (Δ_b/W_b).

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depth is absent up to a depth of 2.5 m. In fact, t_{50} is quite constant and ≈800 s.

The effect of the horizontal distance between balconies on the rate of removal of CO from the street canyon is reported in Fig. 9. To analyse this effect, balcony depth must be maintained constant, then the results reported in Fig. 9 refers to numerical simulations performed for a balcony depth of 1 m. When distance is equal to zero ($\Delta b = 0$), it is $t_{50} \approx 3000$ s. If the horizontal distance approaches infinity the case corresponds to that in the absence of balconies (flat facades) and therefore t_{50} reduces to ≈ 800 s. The effect of distance becomes significant for values of Δ_b less than 1 m. When the horizontal distance is 2 m or higher t_{50} is constant and equal to the case of absence of balconies.

To generalize the results obtained we have defined some non-dimensional geometrical parameters. First a sort of void fraction (ε_c) of the street canyon, defined as the ratio between empty volume/volume of the street canyon without balconies, was introduced. The empty volume is the volume of the street canyon obtained multiplying width, height and length (W•H•L) of the street less the volume occupied by balconies. Volume of the street canyon without balconies is simply W•H•L. Results previously reported were then reanalyzed in terms of this parameter and reported in Fig. 10.

As observed the void fraction cannot be assumed as a significant geometrical parameter. In fact, different values of t_{50} are observed in correspondence of equal values of the void fraction (Fig. 10) because values of t_{50} depend in a different way from depth and horizontal distance.

In Fig. 11 the dependence of t_{50} from the non-dimensional depth (L_b/W) and the non-dimensional horizontal distance (Δ_b/W_b) is reported. Also t_{50} is reported as normalized value by dividing for t_{50} in case of absence of balconies. This diagram is useful to individuate the real cases when balconies can have an effect on the mass transfer rate in the street canyon and, therefore, on the air quality. As observed there is an area of L_b/W and Δ_b/W_b values in which the balconies have an effect on the wash-out process. The area is in the range $\Delta_b/W_b < 0.3$ and $L_b/W > 0.05$. In this range of values balconies can increase the t_{50} by a factor up to 4 times that evaluated in the absence of balconies.

The effect of balconies on wash out rate can be explained from the observation of the flow fields inside the canyon in the different cases. In particular Fig. 5 shows how the presence of continuous balconies determines strong and well defined recirculation zones inside each part of the canyon, leading to a slower wash out with respect to the cases with horizontally separated balconies, particularly in the bottom volume. The flow field inside the canyon in the case of separated balconies produces a greater mass transport between the different zones of the canyon and this is due to the three dimensional features of the flow field. This leads to a less relevant effect of the presence of separated balconies as observed in the wash out curves (Fig. 7). It is worth to remark that the vortex structures induced by the presence of continuous balconies or balconies with low horizontal spacing, cause a significant difference in the wash out time among the different zones in the street canyon (Fig. 12). Such difference is not present in the case of separated balconies with a horizontal spacing greater than 1 m as again shown in Fig. 12. Furthermore, it must be noted that the upper zone of the canyon has a fast wash out time in the case of continuous balconies but the total volume washes out much slower due to the recirculation structures in the lower zones. Also such

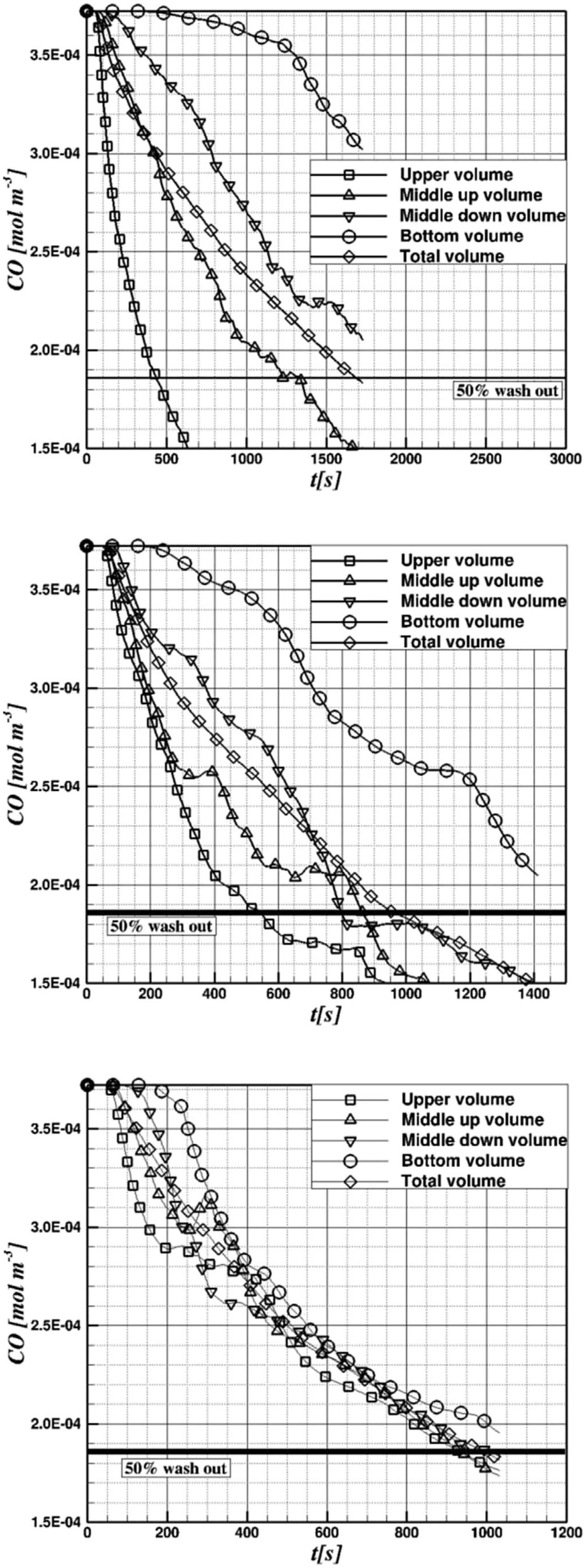

Fig. 12. Spatially averaged concentration of CO in different zones of the street canyon with time (balcony depth = 1 m in all the cases). Up: continuous balconies (horizontal distance = 0); middle: horizontal distance = 0.5 m; bottom: horizontal distance = 2 m.

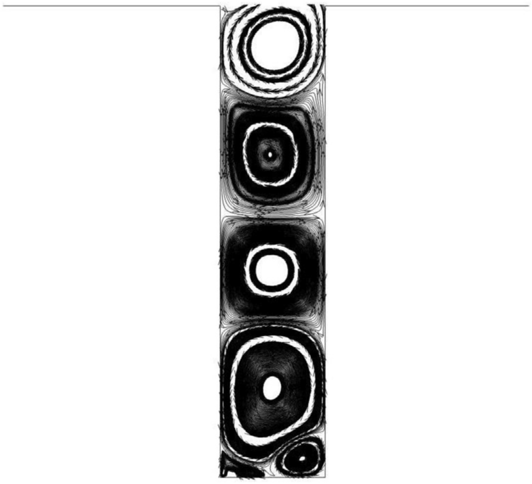

Fig. 13. Streamlines inside the street canyon without balconies assuming flat facades and equivalent width ($H/W_e = 4.5$). To be compared with Fig. 5 up.

behaviour can be linked to the vortex dynamics inside the canyon that, as shown in Fig. 6, is essentially 2D in the case of continuous balconies, differently from the case of separated balconies where a stronger 3D flow field, and then a more relevant mass transfer between the different zones of the canyon, is induced.

Finally it is interesting to note that, at least in the presence of continuous balconies, the effect of balconies could be modelled assuming flat facades (without balconies) but introducing an equivalent width defined as: $W_e = W - 2 \cdot L_b$.

As an example in the case of continuous balconies with $L_b = 1$ m, introducing the equivalent width, a narrower street canyon is obtained with $H/W_e = 4.5$. The flow field obtained for this "equivalent" street canyon is reported in Fig. 13. As shown the vortical structures are very similar to those reported in Fig. 5 (up). This occurrence, once, deeply verified, could simplify significantly the simulation of street canyons in which the presence of balconies cannot be neglected. In fact, it would not be necessary to describe the exact geometry of balconies in the computational domain, but each canyon could be modelled as a street canyon without balconies (flat facades) but substituting actual width with the corresponding equivalent width defined above.

4. Conclusions

Balconies present on the façade of a building can have an effect on the air quality in the street canyon. The presence of balconies modifies the flow field inside the canyon and generally reduces the induced turbulence in the canyon. The most relevant effect on the mass transfer rate from the street level to the roof level is the presence, induced by balconies, of several separated vortices in the street canyon that reduce the mass transfer to the above atmosphere. We have verified this effect through the observation of an increase of the wash-out time of the canyon through CFD simulations in the presence of balconies. In real cases this phenomenon can causes the increase of pollutant concentration in the canyon and higher differences in concentration between road and roof levels.

We have simulated, in 3D geometries, a deep street canyon with $H/W = 3$ and a wind direction perpendicular to the street axis. In this case the effect of balconies depends from their depth and by the horizontal distance between balconies. Our results, expressed in terms of non-dimensional geometrical parameters, show that the presence of balconies limit the mass transfer from the bottom volume to the roof top level when $\Delta_b/W_b < 0.3$ and $L_b/W > 0.05$. In this range of values, the wash out time to half the initial concentration of a passive pollutant can increase by a factor of 4.

The aim of the paper was to give a contribution for the assessment of more reliable mass transfer rate to be adopted in operational models. Mass transfer rate are often derived from CFD simulations where the presence of balconies is not considered. Our results suggest that, in the conditions tested in our simulations, and in the ranges $\Delta_b/W_b < 0.3$ and $L_b/W > 0.05$, the mass transfer rate between the street canyon and the above atmosphere in operational models would be adjusted to take in count the effect of balconies.

References

Allegrini, J., Dorer, V., Carmeliet, J., 2013. Wind tunnel measurements of buoyant flows in street canyons. Build. Environ. 59, 315–326.

Barlow, J.F., Harman, I.N., Belcher, S.E., 2004. Scalar fluxes from urban street canyons. Part I: laboratory simulation. Bound. Layer. Meteorol. 113, 369–385.

Bentham, T., Britter, R.E., 2003. Spatially averaged flow within obstacle arrays. Atmos. Environ. 37, 2037–2043.

Berkowicz, R., Hertel, O., Larsen, S.E., Sorensen, N.N., Nielsen, M., 1997. Modelling Traffic Pollution in Streets. Ministry of Environment and Energy, National Environmental Research Institute, Roskilde.

Buccolieri, R., Gromke, C., Di Sabatino, S., Ruck, B., 2009. Aerodynamic effect of trees on pollutant concentration in street canyons. Sci. Total Environ. 407, 5247–5256.

Caton, F., Britter, R.E., Dalziel, S., 2003. Dispersion mechanisms in a street canyon. Atmos. Environ. 37, 693–702.

Chan, A., Au, W.T.W., So, E.S.P., 2003. Strategic guidelines for street canyon geometry to achieve sustainable street air quality – part II: multiple canopies and canyons. Atmos. Environ. 37, 2761–2772.

Chung, T.N.H., Liu, C.H., 2013. On the Mechanism of Air Pollutant Removal in Two-dimensional Idealized Street Canyons: a Large-Eddy Simulation Approach. Boundary Layer Meteorology. http://dx.doi.org/10.1007/s10546-013-9811-4.

Egorov, Y., Menter, F.R., Lechner, R., Cokljat, D., 2010. The scale-adaptive simulation method for unsteady turbulent flow predictions. Part 2: application to complex flows. Flow Turbul. Combust. 85, 139–165.

Gromke, C., Buccolieri, R., Di Sabatino, S., Ruck, B., 2008. Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations – evaluation of CFD data with experimental data. Atmos. Environ. 42, 8640–8650.

Hamlyn, D., Britter, R., 2005. A numerical study of the flow field and exchange processes within a canopy of urban-type roughness. Atmos. Environ. 39, 3243–3254.

Hotchkiss, R.S., Harlow, F.H., 1973. Air Pollution Transport in Street Canyons. Technical Report. U.S. Environmental Protection Agency, p. 78. EPA-R4-73-029, NTIS No. PB-233 252.J.

Lee, P.J., Kim, Y.H., Jeon, J.Y., Song, K.D., 2007. Effects of apartment building fac-ade and balcony design on the reduction of exterior noise. Build. Environ. 42, 3517–3528.

Lignarolo, L.E.M., Lelieveld, C.M.J.L., Teuffel, P., March 3-5, 2011. Shape Morphing Wind-responsive Facade Systems Realized with Smart Materials Adaptive Architecture. An International Conference, London, UK.

McHugh, C.A., Carruthers, D.J., Edmunds, H.A., 1997. ADMS-urban: a model of traffic, domestic and industrial pollution. Int. J. Environ. Pollut. 8 (3–6), 666–674.

Menter, F.R., Egorov, Y., 2010. The scale-adaptive simulation method for unsteady turbulent flow predictions. Part 1: theory and model description. Flow Turbul. Combust. 85, 113–138.

Mohamed, M.F., Prasad, D., King, S., Hirota, K. The impact of balconies on wind induced ventilation of singlesided naturally ventilated multi-storey apartment. PLEA2009 – 26th Conference on Passive and Low Energy Architecture, Quebec City, Canada, 22–24 June 2009.

Murena, F., Mele, B., 2014. Effect of short–time variations of wind velocity on mass transfer rate between street canyons and the atmospheric boundary layer. Atmos. Pollut. Res. 5, 484–490.

Murena, F., Di Benedetto, A., D'Onofrio, M., Vitiello, G., 2011. Mass transfer velocity and momentum vertical exchange in simulated deep street canyons. Boundary-Layer Meteorol. 140, 125–142.

Oke, T.R., 1987. Boundary Layer Climates, second ed. Methuen, London.

Salizzoni, P., Soulhac, L., Mejean, P., 2009. Street canyon ventilation and atmospheric turbulence. Atmos. Environ. 43, 5056–5067.

Santiago, J.L., Martin, F., 2008. SLP-2D: a new Lagrangian particle model to simulate pollutant dispersion in street canyons. Atmos. Environ. 42, 3927–3936.

Santiago, J.L., Dejoan, A., Martilli, A., Martin, F., Pinelli, A., 2010. Comparison between large-eddy simulation and Reynolds-averaged Navier–Stokes computations for the MUST field experiment. Part I: study of the flow for an incident wind directed perpendicularly to the front array of containers. Boundary-Layer Meteorol. 135, 109–132.

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Santiago, J.L., Martin, F., Martilli, A., 2013. A computational fluid dynamic modelling approach to assess the representativeness of urban monitoring stations. Sci. Total Environ. 454–455, 61–72.

Sini, J.F., Anquetin, S., Mestayer, P.G., 1996. Pollutant dispersion and thermal effects in urban street canyons. Atmos. Environ. 30, 2659–2677.

Soulhac, L., Perkins, R.J., Salizzoni, P., 2008. Flow in a street canyon for any external wind direction. Boundary-Layer Meteorol. 126, 365–388.

Soulhac, L., Garbero, V., Salizzoni, P., Mejean, P., Perkins, R.J., 2009. Flow and dispersion in street intersections. Atmos. Environ. 43, 2981–2996.

Soulhac, L., Salizzoni, P., Cierco, F.-X., Perkins, R.J., 2011. The model SIRANE for atmospheric urban pollutant dispersion; part I, presentation of the model. Atmos. Environ. 45 (39), 7379–7395.

Soulhac, L., Salizzoni, P., Mejean, P., Perkins, R.J., 2013. Parametric laws to model urban pollutant dispersion with a street network approach. Atmos. Environ. 67, 220–241.

Spalart, P.R., 2000. Strategies for turbulence modelling and simulations. Int. J. heat fluid flow 21, 252–263.

Spalart, P.R., Jou, W., Strelets, M., Allmaras, S., 1997. Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach. In: Advances in DNS/LES, 1st AFOSR Int. Conf. on DNS/LES.

Vardoulakis, S., Fisher, B., Gonzales-Flesca, N., Pericleous, K., 2003. Modelling air quality in street canyons: a review. Atmos. Environ. 37 (2), 155–182.

Vernay, D.G., Benny, R., Smith, I.F.C., 2014. Augmenting simulations of airflow around buildings using field measurements. Advanced Engineering Informatics 28 (4), 412–424.

Yaghoobian, N., Kleissl, J., Paw, U., K, T., 2014. An improved three-dimensional simulation of the diurnally varying street-canyon flow. Boundary-Layer Meteorol 153, 251–276.

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