The pollutant removal capacity of urban street canyons as quantified by the pollutant exchange velocity

A. Kubilay^{a,b,*}, M. K.-A. Neophytou^{a,c}, S. Matsentides^c, M. Loizou^c, J. Carmeliet^{a,b}

^a Chair of Building Physics, Swiss Federal Institute of Technology ETHZ, Zurich, Switzerland

^b Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland

^c Environmental Fluid Mechanics Laboratory, Department of Civil and Environmental Engineering, University of Cyprus, Nicosia, Cyprus

* Corresponding author: Marina Neophytou, Environmental Fluid Mechanics Laboratory, Department of Civil and Environmental Engineering, University of Cyprus. Tel.: +357 2289 2266; E-mail address: neophytou@ucy.ac.cy

Abstract

In this work we investigate the representativeness of the pollutant exchange velocity as a quantitative metric for the actual pollutant removal capacity of a canyon under different pollution emission scenarios. We further explore its sensitivity to a change of the street canyon geometry aspect ratio as well as different exposure regions of interest within a 2-D canyon. We find that the effective pollutant removal capacity as quantified by the pollutant exchange velocity can vary substantially from its reference-nominal value as customarily derived for uniformly-distributed pollutant conditions in the canyon. We specifically find that for the case of the center and leeward wall locations of the source, the pollutant exchange velocity varied substantially exceeding a factor of 2 variations. Furthermore, we find that the highly nonhomogeneous pollutant distribution arising from the different source locations plays an important role in the pollutant removal rate accounting for both the turbulent and convective pollutant transport. As expected, the pollutant-exchange velocity was found to be dominated by the turbulent flux, reaching up to 2 to 3 times the convective pollutant flux at the rooftop level.

Keywords: breathability, city ventilation, urban emission sources, exposure, Computational Fluid Dynamics, Particle Image Velocimetry experiments

1. Introduction

Urban air quality and its impact on civilian health is becoming an increasingly important consideration in the planning and policy-making for healthy and climate-change resilient cities. Design of mitigation strategies for urban pollution exposure requires understanding of how air pollution from emission sources disperses within urban streets, e.g. at what rate it escapes from or accumulates within the streets. Air ventilation within urban street canyons is of rising importance mainly due to its link to the pollutant removal capacity of street canyons and subsequently to the long-term air pollution exposure of citizens. Different measures to quantify the pollutant removal capacity have been proposed such as breathability (Neophytou and Britter 2005; Panagiotou et al. 2013; Neophytou et al. 2014) and mean age of air (Ramponi et al. 2015; Buccolieri et al. 2015). Such measures have been proposed mainly from the view point of characterizing on a bulk basis an urban street canyon itself (as part of a city) thus assuming some idealized prototype scenarios particularly concerning the pollution sources.

This document is the accepted manuscript version of the following article: Kubilay, A., Neophytou, M. K. -A., Matsentides, S., Loizou, M., & Carmeliet, J. (2017). The pollutant removal capacity of urban street canyons as quantified by the pollutant exchange velocity. *Urban Climate*, 21, 136-153. <http://doi.org/10.1016/j.uclim.2017.06.003>

This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

The air flow and pollutant dispersion within and above an urban street canyon is substantially determined by the presence of a shear layer generated at the rooftop level as well as the recirculation flows within the canyon. Shear layers with different thickness can be observed depending on the packing density of the canyons and additional roughness arising mainly at the roof surfaces. The nature of the shear layer at the rooftop level, its level of unsteadiness and thickness, determines the mean convective and turbulent fluxes through that level. The turbulent fluctuations within the shear layer are governed by coherent turbulent structures, which interact with each other across a wide range of spatial and temporal scales (Paterna 2015). Such turbulent structures within shear layers can have a significant influence on pollutant and heat removal mechanisms in the built environment (Liu and Wong 2014). Furthermore, the flow structures can also be different within street canyons depending on the geometry of the canyon e.g. on its aspect ratio, resulting in single or multiple recirculation regions within the street canyon. In addition, more complex and multi-scale effects can take place in urban atmospheres e.g. due to complex topographic terrain and land use variations (Fernando 2010).

There has been substantial discussion in the literature on the urban air flow within street canyons under different conditions, e.g. for dense pollutant dispersion within isolated streets (Baratian-Ghorghi and Kaye 2013), the flow and dispersion in unstable thermal stratification (Mei et al. 2016), and the impact of building configurations in isolated deep street canyons (Ng and Chau 2014). Recently emphasis has been directed particularly to the capacity of urban street canyons to remove pollutants produced within (e.g. emissions from traffic or buildings). There are several definitions of exchange velocity in the literature that characterizes and quantifies the pollutant removal rate, e.g. air-exchange velocity which takes into account only the air-flow rate going out of a defined control volume (Bentham and Britter 2003; Li et al. 2005; Liu et al. 2005; Cheng et al. 2008; Moonen et al. 2011; Panagiotou et al. 2013) or pollutant-exchange velocity which takes into account also the distribution of pollutant concentration (Buccolieri et al. 2015; Liu et al. 2005; Cheng et al. 2008). Such metrics are used to compare the influence of different building morphologies and wind-flow conditions on pollutant transport in urban areas. A summary of various studies on pollutant removal from street canyons and reported air-exchange velocities is given in Table 1 (Neophytou et al. 2014), where u_e denotes the air-exchange velocity and u_{ref} the reference velocity. The use of air-exchange velocity is practical as it can be obtained directly from air-flow simulations or measurements as a bulk air volume flux exchange rate per unit area of flow out of a considered control volume. The studies performed by Liu et al. (2005), Cheng et al. (2008) and Mirzaei and Haghighat (2011) have considered distinctly air-exchange velocity and pollutant-exchange velocity. Their analyses indicate different variations of these two exchange velocities to a certain variation in street-canyon aspect ratio. However, no direct evaluation is made comparing the reliability of the two exchange velocities in terms of the pollutant removal. Furthermore, even though the air-exchange velocity can be taken as a measure for ventilation efficiency of street canyons, no clear insight, either from theoretical or experimental evidence, is given that the rate of pollutant removal is directly related to air-exchange velocity.

Numerical simulations using Computational Fluid Dynamics (CFD) and experimental studies have been performed extensively in the literature to address wind flow and pollutant dispersion within the built environment. Reviews of CFD studies for pollutant dispersion is provided by Di Sabatino et al. (2013), Tominaga and Stathopoulos (2013), Blocken (2014) and Lateb et al. (2016). The most common models for air flow in urban environments are based on the Reynolds-averaged Navier-Stokes (RANS) equations which describe essentially the ensemble-average of the time-varying field. In the past, specific deficiencies of RANS $k-\epsilon$ modeling have been reported (Murakami 1990, 1993; Tominaga et al. 2008a; Tominaga et al. 2008b), such as the overestimation of turbulence kinetic energy in the stagnation region at the windward facade, and the overprediction of the size of the wake and the location of reattachment due to the underestimation of turbulence kinetic energy in the wake of the building. As a result, pollutant dispersion studies using RANS models of turbulent flow over street canyons often show a limited success in predicting the turbulent flow, especially in the shear layer region. Large Eddy Simulation (LES) is an improved alternative to RANS in obtaining more accurately air velocity fields when large-scale unsteadiness is significant, as in bluff-body flows. However, their substantial computational cost is making them more

difficult to use for extensive detailed flow analyses in practical applications. Experimental analyses of the air flow mostly focus on the main flow features and turbulent coherent structures around isolated surface-mounted bluff bodies (Castro and Robins 1977; Hussein and Martinuzzi 1996; Martinuzzi and Tropea 1993; Schofield and Logan 1990) as well as turbulent flows around a matrix of cubes with spatial flow periodicity (Meinders and Hanjalić 1999). Furthermore, there is considerable amount of experimental research focusing on measurements of air pollutant concentrations (Caton et al. 2003; Chang and Meroney 2003; Mavroidis et al. 2003; Park et al. 2004; Salizzoni et al. 2009; Hajra et al. 2013) as well as pollutant fluxes from building surfaces (Barlow et al. 2004) inside wind tunnel experimental set-ups. Such studies can also be used as benchmark cases for the validation and the inter-comparison of various numerical urban air flow models. Comparisons of various numerical models with experiments show that, in street canyon cases where the pollutant removal at the roof level is mainly due to turbulent transport, deficiencies in the RANS $k-\epsilon$ models lead to an underestimation of the turbulent diffusion of pollutants in the shear layer (Walton et al. 2002; Liu et al. 2005).

In this work we investigate the representativeness of this bulk street canyon breathability for the actual pollutant exposure of pedestrians under certain pollution emission scenarios and its sensitivity to various street canyon aspect ratios and regions of interest within the canyon. This is performed by using unsteady numerical simulations for turbulent pollutant dispersion from a release source located within the street canyon. The wind-flow field is based on existing results on a 2-D vertical plane obtained from relevant laboratory experiments using Particle Image Velocimetry (Neophytou et al., 2014) within and above the street canyons. In this way, possible discrepancies related to the prediction of the time-averaged flow field within the shear layer near the critical street canyon rooftop region associated with the RANS turbulence models are avoided.

The present paper is organized as follows: section 2 presents the methodology used, giving specifications of the numerical model for the pollutant dispersion and the associated tests for the pollutant release as well as the background information on the existing results from water-channel measurement. In section 3, the results for the pollutant dispersion in an idealized homogeneous street canyon with an aspect ratio 1 are presented; a sensitivity analysis is also presented accounting for different pollutant locations, street canyons of different aspect ratios and various control volumes of interest within the street canyon. Finally, section 4 provides a general discussion of the results while section 5 provides the concluding remarks of this research work.

2. Methodology

In this work we use unsteady numerical simulations of turbulent pollutant dispersion arising from a source release located within a street canyon; the dispersion simulations are driven by a velocity flow field obtained from existing experimental results. Fig. 1 depicts schematically the overall methodology.

2.1 Unsteady numerical simulations of pollutant transport

The unsteady pollutant transport is described by the following advection-diffusion equation:

$$\frac{\partial \bar{C}}{\partial t} + \frac{\partial (\bar{C} u_i)}{\partial x_i} - \frac{\partial}{\partial x_i} \left(D_t \frac{\partial \bar{C}}{\partial x_i} \right) = S \quad (1)$$

where C denotes the pollutant concentration, u_i the velocity component obtained from water-channel measurements (Neophytou et al. 2014) in the direction of the Cartesian coordinate x_i ($i = 1, 2$), D_t the turbulent diffusivity, S the source term. The overbar denotes Reynolds averaging. Note that, in Eq. (1), the molecular mass flux is assumed negligible

compared to the convective and turbulent mass fluxes. The turbulent flux is modeled with the gradient-diffusion hypothesis, where the turbulent diffusivity is computed using the expression $D_t = \nu_t / Sc_t$, where ν_t denotes the turbulent viscosity and Sc_t the turbulent Schmidt number. Past research work showed that, due to the underestimation of turbulence kinetic energy in RANS models, lower Sc_t values may give better results as it compensates the deficiency of RANS models by increasing the contribution of turbulent mass flux (Gousseau et al. 2011; Tominaga and Stathopoulos 2007). In the present study, the air velocity field is obtained from measurements and, therefore, the turbulent Schmidt number Sc_t is set to the commonly-used value of 0.7 (Tominaga and Stathopoulos 2007). Turbulent viscosity field ν_t is obtained from the mean velocity gradients and the Reynolds stress components using the Boussinesq hypothesis (Boussinesq 1887).

In the numerical simulations, the velocity field obtained from the water-channel measurements is used as input in Eq. (1), which is solved using the finite volume code OpenFOAM® 2.3. For the advection-diffusion equation of pollutant transport, the pollutant concentration is taken zero at the inlet. Outlet boundary is a pure convective outlet with the normal gradient of concentration, $\partial C / \partial n$, being zero. On building walls, pollutant has no deposition or reaction with the surface. Therefore, on the walls, surface-normal gradient, $\partial C / \partial n$, is zero. For the velocity on the walls, no-slip condition is applied. Time step for the unsteady simulations of pollutant transport is set to 1 ms, which resulted in a maximum Courant number of 0.3. Second-order discretization schemes are used for both the convection terms and the diffusion terms of Eq. (1).

2.2. The flow field driving the numerical simulations for pollutant dispersion

The time-averaged velocity fields and Reynolds stresses driving the numerical simulations for pollutant transport are obtained from the flow measurements which were conducted in a water channel instrumented with a particle image velocimetry (PIV) system (Neophytou et al. 2014). The measurements were conducted in the fully-developed region following a series of idealized street canyons; canyon geometries with different aspect ratio were investigated, each representing a different packing density of building arrays. Each packing density configuration was formed using six rectangular building arrays and therefore forming five consecutive street canyons spanning the entire width of the water channel, representing a 2-D problem. The measurements were performed in and above the last canyon. The Reynolds number based on the building height and the bulk flow velocity ranged between 19 000 and 25 000 ensuring a fully turbulent regime. Note that, the measured flow field should be non-divergent in order to satisfy Eq. 1. Therefore, in order to check flow continuity, the out-of-plane component is estimated based on the measured in-plane velocity components at each computational cell. It is found that the average continuity error in the computational domain corresponds to 2.3% of the velocity magnitude. Larger continuity errors are found at cells near walls, the largest one corresponding to 5.4%. This is mainly attributed to measurement errors due to laser reflection on surfaces. A further check on the conservation of pollutant amount within the computational domain shows a discrepancy lower than 3.0% between the outlet and source. Therefore, it is concluded that the flow continuity is within acceptable limits.

Fig. 2(a) and (b) show the measured fields of flow speed and turbulence kinetic energy per unit mass, respectively, in the configuration with street canyons of aspect ratio 1. The building height H and the street canyon width W equal 0.06 m, while the bulk velocity U_b equals 0.29 m/s. Fig. 2(c) shows the vertical profiles of the Reynolds stress components along three different horizontal positions in the canyon, whereas Fig. 2(d) shows the approach profiles of streamwise velocity and turbulence kinetic energy. Flow speed within the street canyon is considerably lower compared to the free flow, the maximum speed being 0.13 m/s. The main recirculation region stays within the street canyon and does not extend above the rooftop level. The interaction between the flow in and above the street canyon shows a pattern of a skimming flow regime (Bottema 1993) with an isolated vortex in the street canyon. At the rooftop level there is a thin region with higher turbulence kinetic energy, which is also identifiable by a small jump in high Reynolds-stress as illustrated in Fig. 2(c).

2.3. Characteristics of pollutant sources

The relation between the air-exchange velocity and pollutant-exchange velocity is studied by varying the location of the pollutant source within the street canyon, as well as the street canyon geometry. Fig. 3 depicts the different positions of the local volumetric pollutant sources for the street canyon with an aspect ratio $H/W = 1$. The source position 1 models the pollutants originating at the street level, e.g. pollution due to transportation. The center of the source is located 5 mm away from the ground boundary corresponding to a vertical distance $H/12$. Position 2 and position 4 are similarly located 5 mm away from the leeward and windward walls, respectively. These two positions model pollutants originating from the buildings on each side of the street canyon. Position 3 is located at the center of the street canyon. The main difference between position 3 and other sources is the fact that position 3 is located at the center of the main vortex within the street canyon (see Fig. 2(a)). Therefore, the air velocity in the vicinity of position 3 is lower, as per Fig. 2(a), compared to the other sources. In addition to these local pollutant sources, a homogeneous emission method is considered (Buccolieri et al. 2010; Hang et al. 2009), where the pollutant is emitted by a uniformly distributed rate within the whole street canyon. Pollutant sources are set in such a way that the total emission rate is the same for each source location, whether local or uniformly distributed.

2.4. The pollutant removal process from the street canyons

The investigation of the pollutant removal from the street canyon entails the definition of a control volume, in which the change of pollutant concentration is evaluated. In most studies the control volume is defined as the entire street canyon extending up to the rooftop level. However, based on the application and questions of interest addressed, different - smaller or larger - control volumes may be defined. Furthermore, the physically designated region of a street canyon may become less clear or straightforward when more complex geometries are considered – e.g. pitched-roofed versus flat-roofed buildings.

The pollutant-exchange velocity $u_{e,pollutant}$ is defined as (Panagiotou et al. 2013 and Buccolieri et al. 2015):

$$u_{e,pollutant} = \frac{\int (\overline{Cu_y} + \overline{C'u_y'}) dA}{A \langle \overline{C} \rangle} \quad (2)$$

where the numerator denotes the total pollutant flux through a control volume across the area A , i.e. the sum of the mean convective and turbulent pollutant fluxes. C' denotes the fluctuating part of pollutant concentration, u_y' the fluctuating part of the vertical velocity and $\langle \overline{C} \rangle$ the pollutant concentration spatially-averaged over the control volume.

The air-exchange velocity $u_{e,air}$ describing the mean convective exchange fluxes at the rooftop level is defined as (Bentham and Britter, 2003):

$$u_{e,air} = \frac{1}{2W} \int_{-W/2}^{+W/2} |\overline{u_y}| dx \quad (3)$$

where W denotes the width of the street canyon, u_y the vertical velocity and x the main flow direction; the overbar denotes Reynolds averaging.

The air-exchange velocity defined in Eq. (3) only accounts for the convective air exchange flux, and does not consider dispersion and removal of pollutants from the control volume. On the other hand, the pollutant-exchange velocity is a direct measure for the actual removal of the pollutants from the street canyon both by convection and turbulence. In this paper, we address the question whether the air-exchange velocity can be used as a measure to evaluate the pollutant removal from a street canyon.

3. Results

3.1. Reference street canyon

In the transient analysis of pollutant dispersion within the street canyon, the pollutant sources are switched on for a finite duration of 60s in order to model the accumulation of the pollutant in the street canyon until the average pollutant level reaches a steady-state condition. After 60s the pollutant source is switched off and the pollutant distribution is monitored for an additional 40s. The spatially-averaged concentration value in the street canyon is normalized with the reference concentration C_0 defined as:

$$C_0 = \frac{Q_e}{HWU_b} \quad (4)$$

where Q_e is the pollutant source rate in kg/s. Fig. 4(a) shows, as an example, the time evolution of the normalized spatially-averaged concentration in the reference street canyon with unity aspect ratio when a pollutant source is located at the bottom of the street canyon (position 1). The control volume for spatial averaging is the whole street canyon. The evolution of the concentration can be distinguished in three stages: A (accumulation), B (steady state) and C (decay). During stages A and B ($t = 0-60$ s), the emission rate from the pollutant source is constant and the spatially-averaged concentration increases until the pollutant removal rate equals the emission rate. During stage B ($t = 40-60$ s), the removal and emission rates are equal and, as a result, a constant concentration level is attained. During stage C ($t = 60-100$ s), the source is switched off, and as a result, the spatially-averaged concentration decreases. Stages A and C exhibit a similar exponential behavior with equal time constants in magnitude; one in accumulation mode (increasing form) and the other in decaying mode (decreasing form). This is due to the fact that the air velocity field governing the accumulation and decay of the concentration remains the same in both cases.

3.2. The influence of pollutant source location on the pollutant removal capacity

3.2.1. Pollutant concentrations

Fig. 5 shows the contours of normalized concentration during steady conditions (stage B in Fig. 4(a)) within the street canyon with aspect ratio 1 for different source locations: a) near ground level in the street, b) near the leeward wall, c) at the center of the street canyon, d) near the windward wall and finally e) as a uniformly distributed pollutant source. For local pollutant sources (a – d), the resulting spatial distribution of concentration is substantially influenced by the location and the concentration decreases with distance from the source. High concentration regions around the source extend further in the direction of the mean flow. For case (c) with the local source at the center of the street canyon, the pollutant concentration is the highest at the nearly-stagnant region of the vortex. For the case of uniformly distributed emission, the concentration field is more homogeneous compared to the ones with local sources.

Fig. 6(a) shows the time evolution of the spatially-averaged pollutant concentration during stage A in the case of the street canyon with aspect ratio 1 for different source locations. The control volume for spatial averaging is the whole street canyon. The highest steady state concentration is found for the source located at the center of the street canyon. At the center of the street canyon, the wind velocity is low and, therefore, the main mechanism for pollutant dispersion is turbulent diffusion, which is much slower than convection. The case with the source near the leeward wall has the lowest spatially-averaged concentration, which is explained by the fact that most pollutants do not flow back into the street canyon, but are directly removed. Fig. 6(b) presents the time evolution of the spatially-averaged concentration normalized with the maximal concentration on a semi-log scale. Two distinct removal rates are observed: an initial rate that can be steeper or shallower compared to the final slope. The final slope is similar for all source locations and is controlled by the air velocity field. The differences in initial slope can be attributed to different importance of local transport mechanisms, i.e. convective and turbulent diffusive. The slope at the end of the process represents the time constant of the pollutant-removal process. The initial slope is less steep for the source located at the center of the street canyon, due to the fact that the pollutant remains first trapped in the center of the street canyon vortex and is only transferred later from the vortex outwards mainly by turbulent diffusion. The other cases with sources located in the outer area of the street canyon show steeper initial slopes, which is attributed to the fact that the pollutants in the outer zone are more easily removed by convection than compared with the pollutants in the inner zone of the vortex, which have to be removed by turbulent diffusion.

3.2.2. Turbulent and convective pollutant fluxes

Fig. 7 shows the time evolution of the convective and turbulent diffusion parts of the pollutant mass flux at the rooftop level, normalized by reference pollutant flux $q_0 = C_0 U_b$. The control volume for spatial averaging is the whole street canyon. The total pollutant flux out of the control volume at steady state is the same for all cases, since it depends only on the source emission rate and flow field, which is identical for all cases. However, the contributions from the convective and turbulent diffusion fluxes differ for each case. It is found that the turbulent diffusion flux is in all cases dominant compared to the convective flux. The highest difference between the fluxes is found for the source located at the center of the street canyon, where the turbulent diffusion flux is found to be about 2 times larger than the convective flux. For the other source locations, the ratio of the turbulent over the convective flux is slightly smaller ranging between 1.6-1.7. We notice further that the time to reach the steady-state flux is different for the different source locations. Specifically, in the scenario with the source located at the center of the street canyon, it takes a considerably longer time to reach steady state compared to the other source locations. The fluxes reach steady state fastest for the case where the source is located near the leeward wall.

3.2.3. Exchange velocities

Fig. 8 shows the normalized convective and total pollutant-exchange velocity including a comparison with the air-exchange velocity $u_{e,air}$ (dashed line) for the different source locations. The control volume for spatial averaging is taken as the whole street canyon. The pollutant-exchange velocity depends highly on the location of the source. In general, local sources positioned on the outer zone outside the main vortex center, i.e. close to the leeward wall, street level and windward wall, show higher pollutant-exchange velocities. The highest pollutant-exchange velocity is observed for the source located near the leeward wall, whereas the lowest is observed for the source located at the center of the street canyon. The pollutant-exchange velocity for the uniformly distributed source lies between the highest and lowest pollutant-exchange velocities. In general, the convective pollutant-exchange velocity is substantially smaller than the total pollutant-exchange velocity, showing the importance of turbulent diffusion in the removal mechanism.

From Fig. 8 it is clear that the air-exchange velocity substantially underpredicts the total pollutant-exchange velocity, with an exception for the case where the source is located at the center of the street canyon. This agreement is however

accidental, since in general, no direct relation between the air-exchange velocity and the total pollutant-exchange velocity is observed. Only in the case where the source is uniformly distributed, the air-exchange velocity agrees well with the convective part of the pollutant-exchange velocity. From Eqs. 2 and 3 it becomes clear that in the situation of a uniform concentration distribution in the street canyon, the uniform concentration can be removed both from numerator and denominator of the convective pollutant exchange velocity, leading to the definition of the air-exchange velocity.

3.3. The influence of the street canyon aspect ratio on the pollutant removal capacity

In this part, the influence of the street canyon aspect ratio H/W on the pollutant removal capacity is studied. In particular, a narrower and a wider street canyon than the reference street canyon with unity aspect ratio are considered. Fig. 9 shows the measured flow fields (Neophytou et al. 2014) for the street canyons with aspect ratio 2 and 0.43. It is worth noting that compared to the corresponding results for the street canyon with unity aspect ratio (Fig. 2(a)), the center of the main vortices within the canyons shifted. In the narrower street canyon (aspect ratio 2), the center of the main vortex moved from the street canyon center towards the rooftop level, whereas in the wider street canyon (aspect ratio 0.43), the center moved towards the windward facade.

Fig. 10(a) compares the time evolution of the spatially-averaged pollutant concentration within the street canyon for the different aspect ratios. The control volumes for spatial averaging are taken as the whole street canyon for each case. A uniformly distributed emission source over the entire street canyon was considered. The values are normalized with the reference concentration C_0 . The highest spatially-averaged pollutant level is found in the narrowest street canyon (aspect ratio 2), where the pollutant concentration is still increasing after 40s. The spatially-averaged concentration in the wide street canyon (aspect ratio 0.43) is the lowest. Fig. 10(b) compares the time evolution of the spatially-averaged pollutant concentration normalized with the maximal concentration on a semi-log scale. As the street canyon becomes narrower, i.e. the aspect ratio increases, the slope of the curve decreases or time constant increases, indicating the pollutant removal process becomes slower.

Fig. 11 confirms this result by comparing the exchange velocities for street canyons with different aspect ratios. The wider street canyon with aspect ratio 0.43 shows the highest total pollutant-exchange velocity, while the narrow street canyon with aspect ratio 2 the lowest. For all aspect ratios, the convective part of the pollutant-exchange velocity is much lower than the total one indicating again the importance of turbulent diffusion in the pollutant removal process. We also observe that the air exchange velocity underestimates significantly the total pollutant-exchange velocity for all aspect ratios. As indicated before the air-exchange and convective pollutant-exchange velocities agree with each other, when the pollutant distribution is quite uniform, as is the case for the studied case with a uniform pollutant source. These results indicate again that the air-exchange velocity cannot be used in general to characterize the pollutant removal potential.

Fig. 12 summarizes all results of the pollutant-exchange velocity as function of the aspect ratio H/W and compares these with the air-exchange velocity. The total pollutant exchange velocity increases with decreasing aspect ratio of the street canyon for all cases, showing that pollutants can be more effectively removed from wider than narrow street canyons. The results show that the air-exchange velocity underestimates the total pollutant exchange in all cases. It is clear that the pollutant-removal mechanism is driven by two flow features, i.e. convection and turbulent diffusion, where the latter in the street canyon case is dominant. This is mostly due to the fact that the air velocity fields above and below the rooftop level are quite separated, resulting in a skimming flow regime (Oke 1988; Neophytou et al. 2014), and the air and pollutant exchange at the rooftop level is governed largely by turbulence and turbulent diffusion, respectively.

3.4. The influence of the choice of considered region of interest

In this part we study the influence of the choice of considered region of interest, that is the control volume in the analysis, which may reflect different interests: (1) a control volume at the lower level of the street canyon extending only up to half-height of the canyon for studying the pedestrian-level pollution; (2) a control volume consisting of the whole computational domain for studying a larger scale that takes into account the pollution from upstream sources. In this study, we focus on the pedestrian interest and compare results for control volumes defined by the entire street canyon (H), from bottom to half height ($H/2$) and from bottom to quarter height ($H/4$).

In Fig. 13, the convective and total pollutant-exchange velocities are compared with the air-exchange velocity for the different control volumes. A street canyon with an aspect ratio 1 is considered with a pollutant source located at the street level. The total pollutant-exchange velocity is the highest for the control volume with height equal to H , and decreases with the height of the control volume. This shows that it is more difficult to remove pollutants from the lower part of the street canyon. It becomes also clear that the pollutant removal mechanisms due to the different relative contributions of the convective or turbulent fluxes will be different for different control volumes. For the control volume of half height, the convective part equals the total one, meaning the main removal mechanism is convective. This becomes clear in Fig. 14, which compares the profiles of vertical velocity along the three horizontal lines located at the upper boundary of each control volume. The vertical velocities are the highest for control volume with height $H/2$. In this case, polluted air is removed mainly by convection from the control volume and the contribution of turbulent diffusion is limited. Fig. 13 also shows that air-exchange velocity overestimates significantly the total pollutant-exchange velocity for the control volumes defined by half-height ($H/2$), while it underestimates totally for the height H . Overestimation can be explained by the fact that the air-exchange velocity considers only the air-flow rate through a plane. Magnitude of the flow velocity is indeed highest at $y = H/2$ (see Fig. 14). In reality, the flow recirculation within the street canyon leads pollutants in the higher part of the street canyon back in the lower half of the canyon, having a decreasing effect on pollutant removal. This mechanism is taken into account by the pollutant-exchange velocity.

4. Discussion

In this work the pollutant removal capacity is investigated, motivated by an interest to assess the long-term outdoors pollution exposure of civilians. The gross breathability of the street canyon as quantified by the air exchange velocity has been used so far in the literature as a quantitative metric of the pollutant removal capacity, assuming a basic scenario for the emission source that is causing a uniformly distributed pollution field. However, the non-uniformity in pollutant distribution is the most dominant scenario when the pollutant sources are local at different positions within the street canyon. In such cases, the exponential curves of the pollutant levels within the street canyon deviate from a single exponential behavior, which is attributed to the occurrence of local transport mechanisms when the emissions are generated from local sources in the street canyon. In fact, we found a considerable agreement between the time constants of pollutant-concentration curves in street canyons of different aspect ratios with the results of pollutant-exchange velocity, e.g. the steepest slope in Fig. 10(b), which represents the shortest time constant, is for the wider street canyon. However, the use of the time constant as a measure for pollutant removal is not straightforward, since the pollutant-concentration curves do not show a single exponential behavior.

It is important to note that in the present study air velocity fields from laboratory experiments are used in order to exclude the numerical deficiencies related to RANS turbulence modeling, such as in the prediction of the turbulent air flow field characteristics, e.g. deficiencies in the shear layer at the top of the street canyon. This way, more accurate time-averaged

1 flow fields are obtained. However, our approach for pollutant dispersion is still based on the validity of the gradient-
2 diffusion hypothesis for determining the pollutant concentration field given the air flow field. It is noted that the gradient-
3 diffusion approach may be incorrect, when important turbulent fluxes of pollutants occur in a direction opposite to the
4 concentration gradient, which might be the case for the shear layer at the top of the street canyon (Liu et al. 2005; Gousseau
5 et al. 2011). In future research, this assumption should be analyzed in more detail. Having said that, it can be argued that the
6 conclusion regarding the two exchange velocities is still valid, as the air-exchange velocity shows discrepancies even when
7 the main pollutant-removal mechanism is convection as in section 3.4 for different definitions of control volume.

8
9 The scope of this study covers only forced convection, and not other conditions such as low wind speeds and high surface
10 temperatures in the street canyon. Forced convection leads to the formation of a strong shear layer at the top of the street
11 canyon, preventing convective pollutant exchange. In the case of low wind speeds and high surface temperatures in the
12 street canyon, buoyancy can create strong upwards air flows enhancing the potential for pollutant removal. However, with
13 buoyancy, the velocity fields may become substantially 3-D enabling air flow into the street canyon from the sides of street
14 canyon. It is also noted that in the present study, background pollution is assumed to be zero. In reality, the air above the
15 rooftop level can already be polluted and in some cases, the pollutant concentration above the rooftop level can even be
16 higher than within the street canyon, e.g. pollutant source being located on the roof of an upstream building. Furthermore,
17 this study does not differentiate the type or nature of pollutant sources, e.g. domestic, commercial, or emitted from vehicles.
18 In reality, the nature of a pollutant source can have an influence on the dispersion rate and on how critical certain cases are.

19
20 It is noted that in the present study, idealized street canyons, e.g. with equal building heights, flat roofs and without any
21 vegetation, are considered. In the non-idealized, more realistic cases, the air velocity fields within street canyons can be
22 quite different, leading to different exchange velocities. For example, Moonen et al. (2013) shows that the existence of
23 vegetation can lead to increased amount of pollution within the street canyon in certain cases by causing pollutants to be
24 trapped under the trees. Furthermore, the highest aspect ratio in the present study is 2.0. One can assume that, at higher
25 aspect ratios, the general trend will follow the one in Fig. 12. However, the results for localized pollutant sources may differ
26 as the main flow patterns will change. Also, in cases of high-rise buildings, pollutant removal through the vertical side
27 planes will become more significant. These limitations mean that the validity of our conclusions may be limited for more
28 complex cases under realistic conditions, which can be the subject of future research. On the other hand, the approach in the
29 present study is based on the experimental flow field and helps to increase the accuracy in the critical shear layer,
30 characteristic to urban flows, where the removal of pollutants due to turbulent fluxes dominate. Further work is also
31 required to assess measures to enhance pollutant dispersion mechanisms, e.g. through enhancing turbulence or through
32 enhancing pollutant removal by directing fresh air into street canyon by geometrical variations such as varying building
33 heights. Another interesting aspect would be to use the normalized exchange velocity and the associated breathability in
34 combination with the traffic intensity, taking into account air-quality assurance and pollutant exposure, e.g. by
35 controlling/regulating traffic pollution sources.

36
37 Finally, we find that for detailed assessment of the pollutant-removal capacity in urban areas and pollutant exposure, the
38 distribution of pollutant concentration has to be taken into account. If one is interested in the local concentration, the
39 pollutant-exchange velocity is a metric which accounts for local effects and can help with the design of mitigation strategies
40 for urban pollution exposure. The air-exchange velocity, on the other hand, is mainly intended for larger scale studies where
41 simpler street-canyon models are described with average concentrations. This is why it shows large discrepancies when
42 local pollutant sources are used within the street canyon.

5. Conclusions

In this work we investigate the sensitivity of the pollutant removal process to the emission source characteristics in order to assess the range of its representativeness, especially from the view point of outdoor pollution exposure. In particular, the influence of the position of a local emission source, as well as the street canyon aspect ratio and the location of the exposure area of interest on the pollutant removal rate were studied. This was performed by using transient simulations based on an advection-diffusion scalar transport equation, driven by a flow velocity field obtained experimentally; the turbulent pollutant flux is modeled using the gradient-diffusion hypothesis. The air velocity flow field driving the numerical simulations for the pollutant transport is obtained from experimental measurements used as input in order to avoid limitations related to urban turbulent air flow modelling.

Our findings can be summarized as follows below.

The effective pollutant removal capacity as quantified by the pollutant exchange velocity can vary substantially from its reference-nominal value as customarily derived for uniformly-distributed pollutant conditions in the canyon. Specifically, the effect of source location was assessed by investigating different source-location scenarios: at the canyon center, at the leeward and windward wall sides, at street-level and for uniformly-distributed pollution field. We found that for the case of the center and leeward wall locations of the source, the pollutant exchange velocity varied substantially exceeding a factor of 2 variations: below 50% for the case of the center source location and over 200% for the leeward wall source location. The windward and street level sources were close to the case of the uniformly-distributed scenario within 20%. For the other source locations the pollutant exchange velocity was within 10% of its reference-nominal value for uniformly-distributed pollutant conditions in the canyon.

The pollutant removal velocity was also found to be prone to variability of the canyon geometry aspect ratio. Specifically, testing the pollutant removal process for the same source conditions for 3 different aspect-ratio canyons ($H/W=0.5, 1$, and 2) the pollutant removal velocity was reduced to less than 25% of the reference-nominal value in the case of $H/W=2$ and was more than double in the case of $H/W=0.43$. The time constants characterizing the rate of pollutant removal were also found different, showing larger values for the narrower street canyons. Time constants for different source locations within the same street canyon show distinctive initial slopes, which are due to local pollutant dispersion effects around the source location.

Different considerations of control volume, reflecting different exposure area of interest e.g. entire street canyon or only at the pedestrian level, do not appear to have different representativeness in the pollutant exchange velocity - the variability ranged within less than 20%. It is most difficult to remove pollutants at lower levels in the street canyon, possibly due to fact that the recirculation region within the street canyon acts as a means to direct pollutants located at higher parts of the street canyon back towards the lower part.

The rate of pollutant removal from street canyons as expressed through the pollutant-exchange velocity was found to be dominated by the turbulent flux as expected; specifically the turbulent pollutant flux removal was 2 to 3 times larger than the convective pollutant flux at the rooftop level. Similar to the overall pollutant removal, the relative importance of convection and turbulent diffusion as pollutant transport mechanisms depends on the location of the source and the choice of the control volume.

1 As expected, different pollutant removal capacities translate into different steady-state (long-term) pollution exposure levels
2 within the canyon. The long-term pollution levels are lowest by a factor of 2 from the reference-nominal case (i.e.
3 uniformly-distributed) when the source is on the leeward side whereas the pollution levels become 3 times higher when the
4 pollutant source is located near the center of the street canyon.
5
6 The variability of the pollutant removal capacity as seen from the above investigations, needs to be further assessed in more
7 detail for its sensitivity to different canyon geometries, e.g. canyons with variable building heights, with pitched roofs or
8 pilotis, or more complex and realistic urban environments, which is subject of future work.

References

- Baratian-Ghorghi, Z., and Kaye, N.B. 2013. The effect of canyon aspect ratio on flushing of dense pollutants from an isolated street canyon. *Science of The Total Environment* 443:112-122.
- Barlow, J.F., Harman, I.N., and Belcher, S.E. 2004. Scalar fluxes from urban street canyons. Part I: Laboratory simulation. *Boundary-Layer Meteorol* 113 (3):369-385.
- Bentham, T., and Britter, R. 2003. Spatially averaged flow within obstacle arrays. *Atmos Environ* 37 (15):2037-2043.
- Blocken, B. 2014. 50 years of Computational Wind Engineering: Past, present and future. *J Wind Eng Ind Aerod* 129:69-102.
- Bottema, M. 1993. Wind climate and urban geometry. Ph.D. thesis, Eindhoven University of Technology, Eindhoven, The Netherlands.
- Boussinesq, J. 1887. Essai sur la théorie des eaux courantes. *Mémoires présentés par divers savants à l'Académie des Sciences* 23 (1):1-680.
- Buccolieri, R., Salizzoni, P., Soulhac, L., Garbero, V., and Di Sabatino, S. 2015. The breathability of compact cities. *Urban Clim* 13:73-93.
- Buccolieri, R., Sandberg, M., and Di Sabatino, S. 2010. City breathability and its link to pollutant concentration distribution within urban-like geometries. *Atmos Environ* 44 (15):1894-1903.
- Castro, I.P., and Robins, A.G. 1977. The flow around a surface-mounted cube in uniform and turbulent streams. *J Fluid Mech* 79 (2):307-335.
- Caton, F., Britter, R.E., and Dalziel, S. 2003. Dispersion mechanisms in a street canyon. *Atmos Environ* 37 (5):693-702.
- Chang, C.-H., and Meroney, R.N. 2003. Concentration and flow distributions in urban street canyons: wind tunnel and computational data. *J. Wind Eng. Ind. Aerodyn.* 91 (9):1141-1154.
- Cheng, W.C., Liu, C.-H., and Leung, D.Y.C. 2008. Computational formulation for the evaluation of street canyon ventilation and pollutant removal performance. *Atmospheric Environment* 42 (40):9041-9051.
- Di Sabatino, S., Buccolieri, R., and Salizzoni, P. 2013. Recent advancements in numerical modelling of flow and dispersion in urban areas: A short review. *International Journal of Environment and Pollution* 52 (3-4):172-191.
- Fernando, H.J.S. 2010. Fluid Dynamics of Urban Atmospheres in Complex Terrain. *Annual Review of Fluid Mechanics* 42 (1):365-389.
- Gousseau, P., Blocken, B., and van Heijst, G.J.F. 2011. CFD simulation of pollutant dispersion around isolated buildings: On the role of convective and turbulent mass fluxes in the prediction accuracy. *J. Hazard. Mater.* 194:422-434.
- Hajra, B., Stathopoulos, T., and Bahloul, A. 2013. A wind tunnel study of the effects of adjacent buildings on near-field pollutant dispersion from rooftop emissions in an urban environment. *J. Wind Eng. Ind. Aerodyn.* 119:133-145.
- Hamlyn, D., and Britter, R. 2005. A numerical study of the flow field and exchange processes within a canopy of urban-type roughness. *Atmos Environ* 39 (18):3243-3254.
- Hang, J., Sandberg, M., and Li, Y. 2009. Age of air and air exchange efficiency in idealized city models. *Build. Environ.* 44 (8):1714-1723.
- Hussein, H.J., and Martinuzzi, R.J. 1996. Energy balance for turbulent flow around a surface mounted cube placed in a channel. *Phys Fluids* 8 (3):764-780.
- Lateb, M., Meroney, R.N., Yataghene, M., Fellouah, H., Saleh, F., and Boufadel, M.C. 2016. On the use of numerical modelling for near-field pollutant dispersion in urban environments – A review. *Environmental Pollution* 208, Part A:271-283.
- Li, X.-X., Liu, C.-H., and Leung, D.Y.C. 2005. Development of a k- ϵ model for the determination of air exchange rates for street canyons. *Atmospheric Environment* 39 (38):7285-7296.
- Liu, C.-H., Leung, D.Y.C., and Barth, M.C. 2005. On the prediction of air and pollutant exchange rates in street canyons of different aspect ratios using large-eddy simulation. *Atmos Environ* 39 (9):1567-1574.
- Liu, C.-H., and Wong, C.C.C. 2014. On the pollutant removal, dispersion, and entrainment over two-dimensional idealized street canyons. *Atmos Res* 135-136:128-142.
- Martinuzzi, R., and Tropea, C. 1993. The Flow Around Surface-Mounted, Prismatic Obstacles Placed in a Fully Developed Channel Flow (Data Bank Contribution). *J Fluids Eng* 115 (1):85-92.
- Mavroidis, I., Griffiths, R.F., and Hall, D.J. 2003. Field and wind tunnel investigations of plume dispersion around single surface obstacles. *Atmos Environ* 37 (21):2903-2918.
- Mei, S.-J., Liu, C.-W., Liu, D., Zhao, F.-Y., Wang, H.-Q., and Li, X.-H. 2016. Fluid mechanical dispersion of airborne pollutants inside urban street canyons subjecting to multi-component ventilation and unstable thermal stratifications. *Science of The Total Environment* 565:1102-1115.
- Meinders, E.R., and Hanjalić, K. 1999. Vortex structure and heat transfer in turbulent flow over a wall-mounted matrix of cubes. *Int J Heat Fluid Fl* 20 (3):255-267.
- Mirzaei, P.A., and Haghighat, F. 2011. Pollution removal effectiveness of the pedestrian ventilation system. *J. Wind Eng. Ind. Aerodyn.* 99 (1):46-58.
- Moonen, P., Dorer, V., and Carmeliet, J. 2011. Evaluation of the ventilation potential of courtyards and urban street canyons using RANS and LES. *J. Wind Eng. Ind. Aerodyn.* 99 (4):414-423.
- Moonen, P., Gromke, C., and Dorer, V. 2013. Performance assessment of Large Eddy Simulation (LES) for modeling dispersion in an urban street canyon with tree planting. *Atmos Environ* 75 (0):66-76.
- Murakami, S. 1990. Computational wind engineering. *J Wind Eng Ind Aerod* 36 (1-3):517-538.
- Murakami, S. 1993. Comparison of various turbulence models applied to a bluff-body. *J Wind Eng Ind Aerod* 46-7:21-36.
- Neophytou, M.K.-A., and Britter, R.E. 2005. Modelling the wind flow in complex urban topographies: a Computational-Fluid-Dynamics simulation of the central London area. Proceedings of the Fifth GRACM International Congress on Computational Mechanics. In. Limassol, Cyprus, 29 June-1 July.

- 1 Neophytou, M.K.-A., Markides, C.N., and Fokaides, P.A. 2014. An experimental study of the flow through and over two dimensional
2 rectangular roughness elements: Deductions for urban boundary layer parameterizations and exchange processes. *Phys Fluids*
3 26 (8):086603.
- 4 Ng, W.-Y., and Chau, C.-K. 2014. A modeling investigation of the impact of street and building configurations on personal air pollutant
5 exposure in isolated deep urban canyons. *Science of The Total Environment* 468–469:429-448.
- 6 Oke, T.R. 1988. Street design and urban canopy layer climate. *Energ Buildings* 11 (1–3):103-113.
- 7 Panagiotou, I., Neophytou, M.K.A., Hamlyn, D., and Britter, R.E. 2013. City breathability as quantified by the exchange velocity and its
8 spatial variation in real inhomogeneous urban geometries: An example from central London urban area. *Sci Total Environ* 442
9 (0):466-477.
- 10 Park, S.-K., Kim, S.-D., and Lee, H. 2004. Dispersion characteristics of vehicle emission in an urban street canyon. *Science of The Total*
11 *Environment* 323 (1–3):263-271.
- 12 Paterna, E. 2015. Wind tunnel investigation of turbulent flow in urban configurations: a time-resolved PIV analysis. Ph.D. thesis, ETH
13 Zurich, Switzerland.
- 14 Ramponi, R., Blocken, B., de Coo, L.B., and Janssen, W.D. 2015. CFD simulation of outdoor ventilation of generic urban configurations
15 with different urban densities and equal and unequal street widths. *Build Environ* 92:152-166.
- 16 Salizzoni, P., Soulhac, L., and Mejean, P. 2009. Street canyon ventilation and atmospheric turbulence. *Atmospheric Environment* 43
17 (32):5056-5067.
- 18 Schofield, W.H., and Logan, E. 1990. Turbulent Shear Flow Over Surface Mounted Obstacles. *J Fluids Eng* 112 (4):376-385.
- 19 Tominaga, Y., Mochida, A., Murakami, S., and Sawaki, S. 2008a. Comparison of various revised k-ε models and LES applied to flow
20 around a high-rise building model with 1:1:2 shape placed within the surface boundary layer. *J Wind Eng Ind Aerod* 96 (4):389-
21 411.
- 22 Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., and Shirasawa, T. 2008b. AIJ guidelines for practical
23 applications of CFD to pedestrian wind environment around buildings. *J Wind Eng Ind Aerod* 96 (10-11):1749-1761.
- 24 Tominaga, Y., and Stathopoulos, T. 2007. Turbulent Schmidt numbers for CFD analysis with various types of flowfield. *Atmos Environ*
25 41 (37):8091-8099.
- 26 Tominaga, Y., and Stathopoulos, T. 2013. CFD simulation of near-field pollutant dispersion in the urban environment: A review of
27 current modeling techniques. *Atmospheric Environment* 79:716-730.
- 28 Walton, A., Cheng, A.Y.S., and Yeung, W.C. 2002. Large-eddy simulation of pollution dispersion in an urban street canyon—Part I:
29 comparison with field data. *Atmospheric Environment* 36 (22):3601-3613.
- 30 Yang, Y., and Shao, Y. 2006. A Scheme for Scalar Exchange in the Urban Boundary Layer. *Boundary-Layer Meteorol* 120 (1):111-132.

Figures

Fig. 1. Flow chart summarizing the methodology to obtain the two exchange velocities.

Fig. 2. Measurement data obtained from the PIV water-channel measurements for reference street canyon by Neophytou et al. (2014) showing a) magnitude of mean speed and velocity vectors (m/s), b) turbulence kinetic energy per unit mass (m²/s²) and c) profiles of Reynolds stress components along three vertical lines. d) Approach profiles of streamwise velocity and turbulence kinetic energy.

Fig. 3. The different tested positions of the local pollutant source inside the street canyon.

Fig. 4. a) Time evolution of the spatially-averaged concentration within the street canyon and b) Contours of normalized concentration within the street canyon at time instants $t = 0, 1, 5, 10, 20, 60, 61, 65, 70$ and 80 s.

Fig. 5. Contours of normalized concentration during steady conditions within the street canyon with an aspect ratio of 1 for local sources at a) street level, b) leeward wall, c) center, d) windward wall and for e) uniformly distributed emission. Green rectangles indicate the source location for each case.

Fig. 6. Normalized spatially-averaged pollutant levels with a) linear and b) logarithmic scale on the y-axis for different source locations (local or uniform) within the reference street canyon after a uniformly-distributed emission source is activated.

Fig. 7. Normalized a) convective and b) turbulent mass fluxes of pollutant (q/q_0) at the rooftop level for different source locations within the street canyon with an aspect ratio of 1.

Fig. 8. Pollutant-exchange velocities based on convective and total fluxes for different source locations (local or uniform) compared with air-exchange velocity within the street canyon with aspect ratio of 1.

Fig. 9. Measured magnitude of mean speed and velocity vectors (m/s) for street canyons with aspect ratio (H/W) of a) 2 and b) 0.43.

Fig. 10. Normalized spatially-averaged pollutant levels with a) linear and b) logarithmic scale on the y-axis for street canyons with different aspect ratio after a uniformly-distributed emission source is activated within the street canyon.

Fig. 11. Pollutant-exchange velocities based on convective and total fluxes for a uniformly distributed emission source compared with air-exchange velocity within street canyons with different aspect ratio.

Fig. 12. Air-exchange velocity (Neophytou et al. 2014) and pollutant-exchange velocities for different source locations based on convective (empty symbols) and total pollutant fluxes (filled symbols) for street canyons with different aspect ratio.

Fig. 13. Convective and total pollutant-exchange velocities for different control volumes within the street canyon with aspect ratio of 1.

Fig. 14. Profiles of vertical velocity u_y along three horizontal lines, i.e. street canyon top ($y = H$), half height ($y = H/2$) and quarter height ($y = H/4$) within the street canyon with aspect ratio of 1.

Tables

2

3 Table 1. Summary of numerical, experimental and analytical studies on air-exchange velocity in non-dimensional form
4 updated from Neophytou et al. (2014).

Numerical simulations	Packing density [-]	Air-exchange velocity (u_e/u_{ref}) [-]
Hamlyn and Britter (2005)	0.063	0.011
Geometry: regular cube arrays;	0.160	0.009
u_{ref} taken at $z = 2.5H$	0.440	0.003
Liu et al. (2005)	0.333	0.030
Geometry: street canyon arrays;	0.500	0.050
u_{ref} taken as the mean free-surface velocity	0.666	0.050
Li et al. (2005)	0.333	0.032
Geometry: street canyon arrays;	0.500	0.058
u_{ref} taken as the mean free-surface velocity	0.666	0.060
Cheng et al. (2008)	0.333	0.029
Geometry: street canyon arrays;	0.500	0.059
u_{ref} taken as the mean free-surface velocity	0.666	0.062
Panagiotou et al. (2013)	0.360	0.015
Geometry: real inhomogeneous urban geometry;	0.390	0.047
u_{ref} taken at $z = 2.5H$ (H : average building height,	0.450	0.013
packing density defined locally)	0.680	0.005
Laboratory experiments		
Caton et al. (2003)	0.500	0.026
Geometry: single street canyon;		
u_{ref} taken as the free-stream velocity		
(no ref. height is reported)		
Barlow et al. (2004)	0.667	0.001-0.003
Geometry: street canyon arrays;	0.500	0.002-0.003
u_{ref} taken as the free-stream velocity	0.375	0.002-0.003
(no ref. height is reported)	0.200	0.002-0.004
Salizzoni et al. (2009)	0.500	0.066-0.078
Geometry: street canyon arrays;		
u_{ref} taken as the free-stream velocity		
(no ref. height is reported)		
Analytical work		
Bentham and Britter (2003)	0.063	0.037
Geometry: regular cube arrays;	0.160	0.054
u_{ref} taken at $z = 2.5H$	0.440	0.038

Yang and Shao (2006)	Full range	$f(H/W)$ based on
Geometry: regular urban street canyon;		aerodynamic resistance
u_{ref} taken as the mean		network; while also
free-surface velocity		being function of other
		geometrical parameters

1