# Ventilation and pollutant removal performance in street canyons of different aspect ratios: an LES solution

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## 1 INTRODUCTION

Numerous studies have investigated the relationship between the total resistance across street canyons. Ryu et al. (2007) showed that the friction factor is a function of the pitch ratio. It decreases with decreasing pitch-to-height ratio (PR) of the ribs when the PR is larger than 10 (Han 1984, Liou and Hwang 1992). Whereas, those previous studies were rather limited to low aspect ratios (ARs, reciprocal of PR). In view of the dense buildings in urban areas nowadays, our current understanding is not comprehensive enough to explain the drag in compact cities of high ARs. This study, using idealized two-dimensional (2D) street canyons as the hypothetical urban area, is thus conceived to elucidate the flows and resistance in isolated roughness (AR<0.3), wake interference (0.3<AR<0.7), and skimming flow (AR>0.7) regimes (Oke 1988). The friction factor is peaked at AR = 0.0909 and the flow behaves like a smooth wall when the street canyon is too wide or too narrow.

In addition to the friction factor, the large-eddy simulation (LES) with one-equation subgrid-scale (SGS) model is performed for idealized urban areas to determine the ventilation and pollutant removal performance as functions of the AR. The ARs tested are 0.0667, 0.0909, 0.25, 0.3333, 0.5, 0.6, 0.8, 1, and 2. The air (ACH) and pollutant (PCH) exchange rates are the parameters used to measure the ventilation and pollutant removal performance, respectively. The ventilation performance is found to be enhanced for street canyons of lower AR. The pollutant removal performance, however, is not in line with the ventilation and does not exhibit a linear pattern with the ARs. Their mean and turbulent components are considered separately and the turbulent component is found to dominate the ventilation and the pollutant removal.

## 2 METHODOLOGY

To simulate the wind and pollutant transport, LES with the one-equation subgrid-scale (SGS) model is employed for investigating the ventilation and pollutant removal in idealized 2D street canyons of different ARs. The open-source computational fluid dynamics (CFD) code OpenFOAM 1.6 (OpenFOAM, 2010) is adopted.

### 2.1 *Governing Equations*

The incompressible Navier-Stokes equations in isothermal conditions comprise of the continuity

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

and the momentum conservation

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j = -\Delta P \delta_{i1} - \frac{\partial \overline{\pi}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where $u_i$ are the velocity tensors in the $i$-direction, $x_i$ the Cartesian coordinates, $\Delta P$ the background pressure gradient, $\delta_{ij}$ the Kronecker delta, and $\nu$ the kinematic viscosity. The modified resolved-scale pressure $\pi$ is

$$\overline{\pi} = \overline{p} + \frac{2}{3} k_{SGS} \tag{3}$$

Here, $p$ is the resolved-scale kinematic pressure and $k_{SGS}$ the subgrid-scale (SGS) turbulent kinetic energy (TKE). The overlines represent the resolved scales in the LES. According to the Smagorinsky SGS model (Smagorinsky, 1963), the SGS Reynolds stresses $-\tau_{ij}$ are modeled in the following form

$$-\tau_{ij} = -\left(\overline{u_i u_j} - \overline{u}_i \overline{u}_j\right) = \nu_{SGS}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) + \frac{2}{3} k_{SGS} \delta_{ij} \tag{4}$$

where $\nu_{SGS}$ (= $C_k k_{SGS}{}^{1/2} \Delta$) is the kinematic viscosity, $\Delta$ (= $[\Delta_1 \Delta_2 \Delta_3]^{1/3}$) the filter width, and $C_k$ (=0.07) the empirical constant. The one-equation SGS model

$$\frac{\partial k_{SGS}}{\partial t} + \frac{\partial}{\partial x_i} k_{SGS} \overline{u}_i = -\frac{1}{2} \tau_{ij} \frac{\partial \overline{u}_i}{\partial x_j} + \left(\nu + \nu_{SGS}\right)\left(\frac{\partial^2 k_{SGS}}{\partial x_i \partial x_i}\right) - C_\varepsilon \frac{k_{SGS}^{2/3}}{\Delta} \tag{5}$$

(Schumann 1975) is employed to solve the SGS TKE conservation with another empirical modeling constant $C_\varepsilon$ (=1.05). The mass conservation (pollutant transport) equation is

$$\frac{\partial \overline{\phi}}{\partial t} + \overline{u}_i \frac{\partial \overline{\phi}}{\partial x_i} = \kappa \frac{\partial^2 \overline{\phi}}{\partial x_i \partial x_i} \tag{6}$$

where $\phi$ is the pollutant concentration and $\kappa$ the mass diffusivity of the pollutant.

## 2.2 *LES model description*

The LES computational domain consists of an upstream building and a downstream building of equal height $h$, and a shear layer $5h$ aloft (Figure 1a). The shear layer extends $1/2h$ over the leeward and windward buildings constructing a repeated unit of 3D street canyon. The building separation (or street width) is the only parameter being changed to control the AR. The prevailing wind is normal to the street axis representing the worst scenario from the pollutant removal perspective. The homogeneous spanwise direction measures $5h$ in which the variables are averaged to form an idealized 2D street canyon from the three-dimensional (3D) computational domain (Figure 1b).

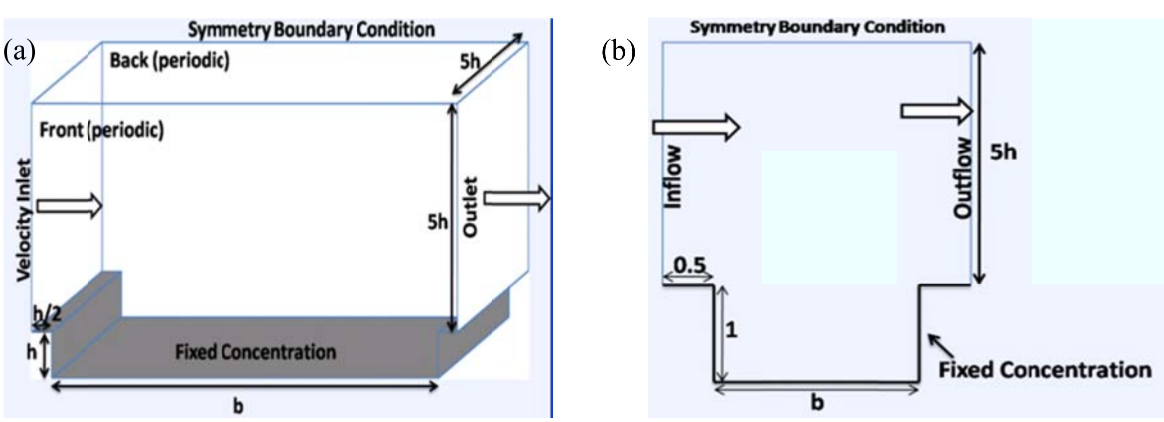


Figure 1 Computational domain of the (a) 3D LES model and (b) averaged 2D LES model

## 2.3 *LES boundary conditions*

Periodic boundary conditions are applied to the flow field in the horizontal directions that represents infinitely long, repeating street canyons. A shear-free boundary is prescribed along the domain top while all the solid boundaries are parameterized using a wall model.

Unlike the wind flow, the pollutant leaves the outlet without any reflection. The pollutant concentration is prescribed to zero at the inflow so no background pollutant is considered. All the solid boundaries at the domain bottom, including the leeward and windward building roofs and facades, and the ground, are set at constant pollutant concentration. Similar to the flow field, a periodic boundary condition is employed in the spanwise direction representing an infinitely long street canyon.

# 3 THEORY

Definitions and the physical meaning of the friction factor, ACH, and PCH are demonstrated below. These values are integrated along the roof level from the ensemble-averaged 2D domain.

## 3.1 *Friction factor*

The prevailing wind flow is driven by the pressure difference $\Delta P$. Counter-balancing the pressure force, the shear stress $\tau$ on the domain bottom is calculated as follows

$$\tau = H \times \frac{\Delta P}{\Delta x} \quad . \tag{7}$$

Here, $H$ is the domain height and $\Delta x$ the streamwise domain extent. Using the equivalent diameter $De$ (= $2AB/(A+B)$) for a rectangular duct of width $A$ and height $B$, air density $\rho$ and mean flow speed in the shear layer $\overline{U}$, the friction factor $f$ is calculated from

$$f = \frac{\tau}{\rho \overline{U}^2 / 2} = \frac{(-\Delta P/\Delta x) De}{\rho \overline{U}^2 / 2} \quad . \tag{8}$$

The physical meaning of the friction factor, as shown in equation (8), is the ratio of the shear force from the ground surface to the kinetic energy per unit volume. Alternatively, the friction factor measures the total force required or the total resistance for the flow to sustain a certain wind speed across the computational domain. The higher the friction factor, the higher the total resistance in the computational domain, the larger force is thus required to sustain the flows over the street canyons.

## 3.2 *Air exchange rate (ACH)*

The ventilation performance can be compared by the ACH (Cheng et al. 2009). It measures the rate of the air transfer across the roof level of the street canyons, i.e. the larger the ACH, the better the ventilation. For incompressible conditions, the wind entraining down into the street canyon equals the wind de-entraining from it, i.e. the overall upward velocity is equal to the overall downward velocity in magnitude along the roof level. Moreover, the ACH has two components: the mean and turbulent components. The mean ACH is defined as the overall upward velocity $\overline{w_+}$ across the roof level

$$\overline{ACH} = \int \overline{w_+} dx \tag{9}$$

while the turbulent ACH is attributed to the roof-level fluctuating velocity

$$ACH'' = \int \frac{1}{2}\sqrt{\overline{w''w''}}dx \qquad (10)$$

## 3.3 *Pollutant exchange rate (PCH)*

The pollutant exchange rate (PCH) is used to compare the pollutant removal performance. It determines the rate of net pollutant removal, i.e. a higher PCH signifies a better pollutant removal performance. The PCH can also be interpreted as the amount of pollutants leaving the street canyon minus the amount of pollutants entering into the street canyon across the roof. Analogous to ACH, PCH is divided into the mean part carried by the mean flow

$$\overline{PCH} = \int \overline{w}\,\overline{c}\ dx \qquad (11)$$

and the turbulent part carried by the turbulent pollutant flux

$$PCH'' = \int \overline{w''c''}dx \qquad (12)$$

# 4 RESULTS AND DISCUSSIONS

## 4.1 *Friction factor*

Figure 2 depicts the relationship between the friction factor and the ARs of street canyons. The LES-calculated friction factor is compared with the predicted average friction factor measured by Han (1984). The results are consistent in the isolated roughness regime. To extend the understanding of the friction factor against AR into the wake interference and skimming flow regimes, the current LES calculates the friction factor in the remaining part of the figure. The friction factor increases with decreasing ARs until reaches its maximum at AR = 1/11 then decreases gradually thereafter. This finding also agree well with our *k*-*ε* modeling results.

In isolated roughness regime, the street canyons of AR 0.0667 and 0.0909 show a decreasing trend when the street is wider. This is a result of reduced obstacles blocking against the flow, leading to a smooth-wall-like behavior. If the prevailing wind is able to entrain down into the street canyon, more energy is required to drive the airflow to sustain a certain wind speed. Therefore, a larger friction factor is resulted with the narrower street in the isolated roughness regime.

In the wake interference regime, when the AR increases, less prevailing wind entrains down into the street canyon so less energy is needed to maintain the flow across the computational domain. The friction factor thus decreases with increasing AR.

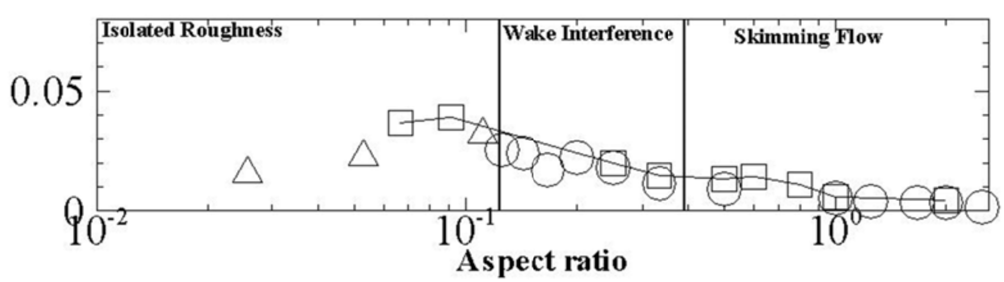


Figure 2 Relationship between friction factor and aspect ratios. Triangle: Han (1984), circle: *k*-*ε* turbulence model, and square: the current LES.

When the buildings are closely packed together in the skimming flow regime, a single, isolated recirculation is spinning inside the street canyon. The pressure difference between the upstream inlet and the downstream outlet is then small leading to a lower total resistance. For more closely packed buildings, less energy is required to drive the recirculation in the street canyon by shear due to the narrower roof.

## 4.2 *ACH*

The relationship between the ACH (normalized by the maximum horizontal velocity and the length of the domain) and the AR is illustrated, together with the LES result and the $k$-$\varepsilon$ solutions from Liu et al. (2011), in Figure 3. All the $\overline{\mathrm{ACH}}$ and ACH" of the LES and $k$-$\varepsilon$ solutions are consistent with each other for ARs smaller than or equal to 0.5. For ARs larger than 0.6 in the skimming flow regime, the $\overline{\mathrm{ACH}}$ compares well between the two numerical solutions, while the ACH"s deviate in which the ACH" obtained from the LES is smaller than that of the $k$-$\varepsilon$ model. However all the total ACH, $\overline{\mathrm{ACH}}$, ACH" show a similar trend in the LES and $k$-$\varepsilon$ results that decreases with increasing ARs.

It is observed that the total ACH is inversely proportional to the AR that is consistent with the common presumption that ventilation is improved in a wider street. We focus on the increasing rate of the ACH with the increasing street width. The ACH increases sharply when the AR is higher in the skimming flow regime. When the street is widened to the wake interference regime, the increasing rate of ACH slows down and is even flattened in the isolated roughness regime.

Due to the fresh air entrainment, the $\overline{\mathrm{ACH}}$ in the isolated roughness regime acts more effectively than does in the wake interference and skimming flow regimes. The $\overline{\mathrm{ACH}}$ has some contribution to the ventilation performance with about 1/5 of the total ventilation rate. In a wider street, the ventilation behaves similarly to a smooth surface; and thus no substantial change in the airflow is observed. It is because most part of the street canyon falls into the redevelopment region in which the flow is parallel to the streamwise flow, with a small recirculation in the leeward side. The air inside the street canyon then exchanges with the air aloft across the roof level in the redevelopment region, promoting to a better ventilation performance. The ACH is normalized by the length of the computational domain; and thus the ACH does not have any noticeable oscillation in the isolated roughness regime.

In both the wake interference and skimming flow regimes, the redevelopment region disappears in which only one recirculation is observed in the street canyon. Therefore, when the street width is reduced, the $\overline{\mathrm{ACH}}$ plays an insignificant role in air exchange due to the tiny air entrainment from the roof down into the street canyon. The vertical mean flow along the roof becomes negligible as it only contributes 10% to the total ACH. The ACH" is therefore the major mechanism for the street canyon ventilation.

Moreover, it is noteworthy that the turbulent component plays a more important role in street canyon ventilation. As the turbulence is generated by the shear stress of the leeward building, the area on the roof level for the generation of turbulence determines the quality of the ventilation. Subsequently, in both the wake interference and skimming flow regimes, the ACH" decreases with increasing ARs. Therefore, to enhance the ventilation performance, turbulence should be promoted in addition to mean wind speed.

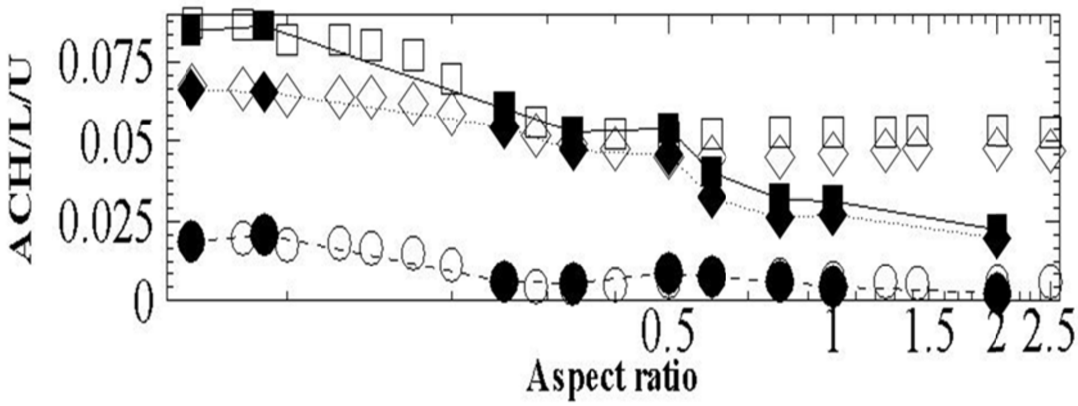


Figure 3 Relationship between normalized ACH and aspect ratios. Circle: $\overline{\text{ACH}}$, diamond: ACH'', and square: total ACH. Empty and filled symbols represent, respectively, the *k*-*ε* modeling and LES results.

4.3 *Pollutant Exchange Rate (PCH)*

The improved ventilation does not necessarily imply the better pollutant removal performance. Figure 4 depicts how the PCH is varied with the ARs. The current LES and *k*-*ε* modeling (Liu et al., 2011) results are comparable, though there are mild derivations among the solutions. The PCH is peaked in ARs around 0.5 and 0.7.

In the isolated roughness regime (0.0667≤ AR≤0.0909), PCH rises due to the reattachment and redevelopment regions in the wider street. The prevailing airflow passed over the leeward building entrains and touches down the ground in the reattachment region if the street canyon is wide enough. The flow in the reattachment region is divided into two parts, which are the upstream wall jet and the downstream redevelopment region. The upstream wall jet traps the pollutants emitted from the ground surface and the leeward facade. The redevelopment region promotes the fresh airflow carrying the pollutants away from the street canyon. As a result, the $\overline{\text{PCH}}$ is relatively important compared with the ARs in other flow regimes. On the other hand, the magnitudes of PCH" are similar to those in the wake interference regime. Again the PCHs are normalized by the length of the computational domain and the flow patterns are similar in the isolated roughness regime, and hence there is no major difference in the PCHs.

In the skimming flow regime (0.5≤AR≤2), the PCH decreases with increasing AR. Under this circumstance, the prevailing wind is unable to entrain down into the narrow street canyon and the roof-level turbulence acts significantly to remove the ground-level pollutants. The reattachment and redevelopment regions are vanished that ends up with one recirculation. In view of the diminished air entrainment from the prevailing wind into the narrow street canyon, the $\overline{\text{PCH}}$ is nearly flattened out in this regime. The energy from the wind shear is particularly used to drive the air inside the street canyon, the area of the roof level decides the strength of the roof-level turbulence to drive the recirculation for pollutant removal. Hence, the lower AR leads to a larger area for the generation of roof-level turbulence, resulting in a higher PCH".

The street canyon of AR 2 is emphasized here due to the two vertically aligned counter-rotating recirculations. The recirculation at the bottom carries the ground-level pollutants to the interface of the recirculations by the mean flow. The pollutants then pass from the lower recirculation to the upper recirculation through their interface by turbulent diffusion. Similar to its counterpart at the bottom, the recirculation at the top drives the pollutants from the interface to the roof, which is then dispersed to the canopy layer by turbulence. The pollutant removal is certainly ineffective because of the weaker wind shear along the roof level and at the interface of the two recirculations.

In the wake interference regime, the total PCH is peaked at the street canyon of AR = 0.5, the PCH drops when the AR is lowered down to 0.33. In this flow regime, the street canyon is long enough so that the pollutants originally removed from the street canyon re-enter into the street canyon following the prevailing wind, leading to the weakened PCH.

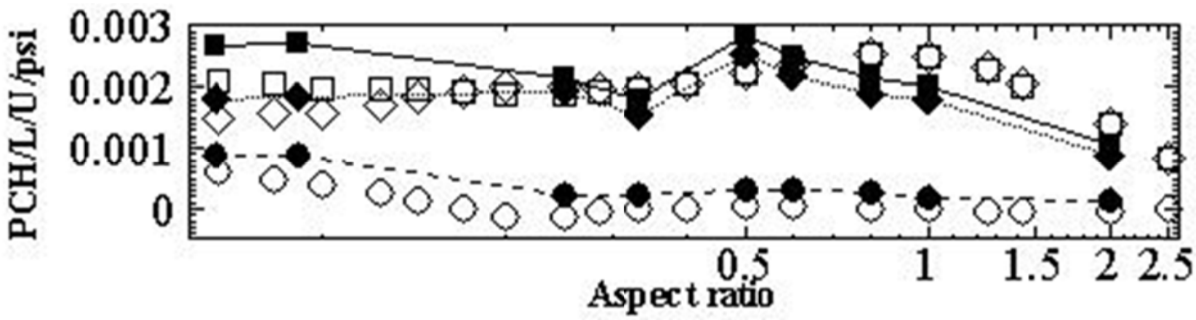


Figure 4 Relationship between normalized PCH and aspect ratios. Circle: $\overline{\text{PCH}}$, diamond: PCH'', and square: total PCH. Empty and filled symbols represent, respectively, the *k*-*ε* modeling and LES results.

## 5 CONCLUSIONS

LES is employed to investigate the total resistance, ventilation, and pollutant removal along the roof level of 2D idealized street canyons. The friction factor is determined that exhibits a peak in-between the isolated roughness and wake interference regimes. The friction factor appears in the AR with a higher total resistance to sustain the flow passing through the computational domain. High pressure gradient is required for the flow passing over the computational domain when the flow is able to entrain down into the street canyon. On the other hand, when the street is too wide or too narrow, the flow acts similarly to that passing over a smooth wall. The ACH shows that the wider the street, the more efficient the aged air removal from the street canyon to the prevailing flow aloft leading to better ventilation. The decreasing rate of the ACH against the ARs is taken into consideration. The PCH behaves differently compared with the ACH. Instead, it increases with decreasing ARs in the skimming flow regime until it reaches the peak PCH in the wake interference regime and decreases thereafter. The decrease in PCH in wider streets is due to the pollutant re-entrainment down into the street canyon by the prevailing wind. Furthermore, the turbulent component plays a more important role in the ventilation and pollutant removal.


## 6 ACKNOWLEDGEMENTS

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