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Impact of building façade geometrical details on pollutant dispersion in street canyons

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1. Introduction

Air quality in urban areas is an important environmental issue worldwide as it contributes to human morbidity and mortality [1,2]. Street canyons are typical elements in urban environments that can represent highly polluted spaces near buildings, due to the low wind speed and accumulation of vehicular pollution inside the canyon. Air pollutants in street canyons can enter the indoor space via window and door openings, ventilation openings and infiltration, this way contributing to indoor air pollution [3]. In addition, high localized pollutant concentrations might cause continuous damage to historic buildings [6,7].

Computational fluid dynamics (CFD) can be used to predict the wind flow and pollutant dispersion in urban street canyons. Previous studies have shown that CFD simulations using the steady Reynolds-Averaged Navier–Stokes (RANS) approach are deficient in modeling the complexities of the wind flow and near-field pollutant dispersion, which motivates the use of large-eddy simulations (LES) [8–12]. Pollutants released in urban areas are transmitted by the interaction between the incoming atmospheric boundary layer and the turbulent flow around buildings, both of which are highly unsteady. The pollutant dispersion process can be seen as the combination of convection, molecular diffusion and turbulent diffusion. In turbulent flows, the molecular mass fluxes are generally negligibly small compared with the turbulent mass fluxes. The accurate reproduction of pollutant dispersion using steady RANS is generally not only limited by the inaccuracies of wind flow prediction, but also by the inaccuracies in modeling turbulent mass transport. With RANS, a turbulent mass transfer is generally computed based on the gradient of the mean concentration, i.e. the gradient-diffusion hypothesis. However, previous studies [13–15] showed that counter-gradient (CG) diffusion can occur, i.e. a turbulent mass flux from low to high concentration areas, contradicting the gradient-diffusion hypothesis. LES on the other hand can predict the turbulent mass transport process more accurately as it captures the large turbulent structures associated with the inherently unsteady wind flow [16,17]. Previous studies on pollutant dispersion around buildings have indicated that LES can reproduce the above-mentioned CG turbulent transport, while steady RANS with the gradient-diffusion hypothesis evidently fails to do so [14,18].

For street canyons, the wind flow and pollutant dispersion processes...
are related to the incoming wind directions. The most widely studied scenarios are those with the wind perpendicular to the street axis, which represent the worst situation for air pollutant dispersion. For short street canyons under such wind direction, corner eddies might be strong enough to inhibit the formation of a stable vortex perpendicular to the street \[19,20\]. A previous study indicated that for an urban street canyon with aspect ratio (roof height \(H/\)street width \(W\)) \(=1\), the canyon middle region had discrete canyon vortices only when the canyon length was divided by roof height \((L/H) \geq 7\) \[21\]. For shorter canyon lengths, the corner eddies affected the establishment of such discrete canyon vortices. Earlier studies on wind flow and pollutant dispersion in long street canyons have investigated the impact of canyon aspect ratios \[22,23\] and roof shape \[24-27\]. However, the vast majority of these studies focused on street canyons with smooth façades without protrusions or recessions. The presence of building façade roughness details like balconies can strongly change the near-building wind flow pattern \[38,39\], surface pressure \[30-34\], and indoor and outdoor air quality \[35,36\], as shown by previous studies on isolated buildings. On the other hand, studies on street canyons with façade geometrical details are scarce \[37-40\]. In those studies that considered pollutant dispersion, the 3D steady RANS approach \[38,39,41\] or scale-adaptive simulations \[40\] were adopted. To the best knowledge of the authors, a systematic investigation of the impact of balconies at the windward façade, leeward façade or both façades on the pollutant dispersion process in street canyons using LES has not yet been performed.

This study aims to provide more insight into the impact of façade geometrical details on the transport process of pollutants in street canyons based on LES simulations. The effective pollutant removal capacity has been evaluated and the contributions of the two main pollutant removal mechanisms, i.e., convective and turbulent diffusion, have been quantified. The focus is on street canyons with balconies.

Section 2 describes the CFD validation study. The computational settings and parameters for CFD simulations are presented in Section 3. Section 4 provides the results of the simulations. Finally, discussion and conclusions are given in Section 5 and Section 6, respectively.

2. CFD validation study

Two sets of CFD validations are conducted in the present study.

2.1. Validation I: Mean pressure coefficients on a building with balconies

For the first part of the CFD validation, atmospheric boundary-layer (ABL) wind tunnel measurements of mean surface pressure coefficients on a building with balconies \[32,42\] are used. As this validation study has been published as a separate paper \[43\], the outline is only briefly mentioned here.

The building dimensions were \(0.152 \times 0.152 \times 0.3\) m\(^3\) (width \(\times\) depth \(\times\) height, at 1:400 scale). Balconies were present at one of the façades and extended along the façade width. The reduced-scale balcony depth was 0.01 m and the height of the balcony parapet walls was 0.0025 m. For the façade with balconies, pressure taps were placed along vertical lines to measure the wind-induced surface pressure. The mean pressure coefficients \((C_p)\) were calculated as:

\[
C_p = \frac{P - P_0}{0.5\rho U^2_c}
\]

where \(P\) is the mean surface pressure, \(P_0\) is the reference static pressure \((= 3.5\) Pa\) and \(\rho\) is the air density \((1.225\) kg/m\(^3\)). \(U_c\) is the reference mean wind speed taken at gradient height \((1.4\) m/s at the reduced-scale height of \(0.625\) m). Three approach-flow wind directions were considered: \(\theta = 0^\circ\) (wind direction perpendicular to the façade with balconies), \(90^\circ\), and \(180^\circ\).

In this validation study, the wind directions \(\theta = 0^\circ\) and \(180^\circ\) are examined. The quality of the grid is measured by the LES index of quality. The result shows that the volume-averaged amount of total kinetic energy resolved is 92.9%, which is larger than the threshold of 80%, indicating a well-resolved computation \[43\]. LES simulations are performed using the commercial CFD code ANSYS Fluent 18.0 \[44\]. The wall-adapting local eddy viscosity (WALE) subgrid-scale (SGS) model \[45\] with the constant \(C_{wale} = 0.325\) is used. The fractional step method is used for non-iterative time advancement. Time discretization and pressure interpolation are second-order. The Werner-Wengle wall functions are employed \[46\]. More detailed information about the computational grids, boundary conditions, and the numerical procedure can be found in Ref. \[43\].

Fig. 1 shows the measured and simulated mean surface pressure coefficients along two lines located at reduced-scale distances of 0.061 m and 0.0015 m from the edge of the façade with balconies. For \(\theta = 0^\circ\), the agreement between the wind tunnel and CFD results along the center line is fair, with an average absolute deviation of 0.027. This deviation is 0.133 for the edge line. For \(\theta = 180^\circ\), a good agreement between the wind tunnel and CFD results is observed for both lines. In this case, the average absolute deviations are about 0.041 and 0.036 for the center line and edge line, respectively. Possible reasons for the small deviations are discussed in detail in Ref. \[43\].

2.2. Validation II: Mean velocities and pollutant concentrations in a street canyon

For the second part of the CFD validation, ABL wind tunnel measurements of mean velocities and mean tracer gas concentrations for generic street canyons \[47,48\] are used. As this validation study has been published as a separate paper \[49\], the outline is only briefly mentioned here.

The street canyon model was composed of two parallel buildings with the dimension of \(1.2 \times 0.12 \times 0.12\) m\(^3\) (length \(\times\) depth \(\times\) height, at scale 1:150). The reduced-scale distance between the two buildings was 0.12 m. The approach-flow was perpendicular to the canyon axis. The tracer gas, i.e., sulfur hexafluoride \((SF_6)\), was released constantly from four line-like sources mounted in the street at ground level \[47\]. Measurement taps were placed along vertical lines at a reduced-scale distance of 5 mm from each of the canyon building façades to sample the local concentration of tracer gas \[50\]. The dimensionless mean \(SF_6\) concentration was calculated using Eq. (2):

\[
C^+ = \left(\frac{U_c}{Q/l}\right)\left(\frac{H}{D}\right)\left(\frac{D}{H}\right)
\]

where \(C\) is the mean \(SF_6\) concentration, \(U_{ref} (= 4.65\) m/s\) is the mean wind speed of the approaching flow at the roof height \(H (= 0.12)\) m, and \(Q/l\) is the \(SF_6\) emission rate per unit length of the line source. The mean vertical velocity components \((W)\) were measured along four vertical lines (reduced scale: \(x/H = 0.083, 0.25, 0.75\) and 0.917) in the \(xz\)-plane that perpendicular to the canyon axis \((y/H = 0.5)\) using laser-Doppler velocimetry \[47\] (Fig. 2).

In the CFD simulations, four line-like sources are mounted at the ground following to their locations in the experiment. The emission rate is assumed to be \(Q = 10\) g/s, as recommended in Ref. \[51\]. The grid resolution is adopted based on a grid-sensitivity analysis reported in Ref. \[49\]. The resulting LES index of quality indicates that the volume-averaged amount of total kinetic energy resolved is 92.8% for the whole volume. LES simulations are performed using the commercial CFD code ANSYS Fluent 18.0 \[44\] and the WALE SGS model \[45\] is employed. Second-order discretization schemes are selected for the energy and \(SF_6\) concentration equations. The other computational settings are the same as in the first validation study (see Section 2.1). More details about the computational grids, settings and parameters can be found in Ref. \[49\].

Fig. 2 compares the wind tunnel and CFD results of the dimensionless mean vertical velocity component \((W/U_{ref})\) along the four vertical lines.
The agreement between the wind tunnel and CFD is considered to be good. The average absolute differences between measurements and CFD along lines $x/H = 0.083$, $0.25$, $0.75$ and $0.917$ are $0.03$, $0.03$, $0.04$ and $0.01$, respectively.

Fig. 3 compares the wind tunnel results and CFD results of $C^+$ along four vertical lines at $y/H = 0$ and $1.25$ near the leeward façade, indicating a close agreement. The average absolute deviations of $C^+$ along the lines at $y/H = 0$ and $1.25$ near the leeward façade are $1.46$ and $1.50$, respectively. These deviations are $0.53$ and $0.14$ for these two lines near the windward façade.

Fig. 1. Validation I: Comparisons between measured and simulated $C_p$ on (a) edge line and (b) center line on the windward façade. (c–d) Same on the leeward façade. Error bars represent the measurement uncertainty reported in Ref. [42].

Fig. 2. Validation II: Comparisons between measured and simulated $W/U_{ref}$ along 4 vertical lines in a vertical plane at $y/H = 0.5$: (a) $x/H = 0.083$, (b) $x/H = 0.25$, (c) $x/H = 0.75$ and (d) $x/H = 0.917$ [49].

Fig. 3. Validation II: Comparisons between measured and simulated $C^+$ along two vertical lines near the leeward façade: (a) $y/H = 0$ and (b) $y/H = 1.25$. (c–d) Same for two vertical lines near the windward façade. Error bars represent the measurement uncertainty reported in Ref. [48].
3. CFD simulations

3.1. List of cases

Four cases are considered (Fig. 4):

1) Case NB: street canyon without balconies;
2) Case BWL: street canyon with balconies positioned at both windward and leeward façades;
3) Case BW: street canyon with balconies positioned only at the windward façade;
4) Case BL: street canyon with balconies positioned only at the leeward façade.

3.2. Computational domain and grid

For all balconies, the depth is 1 m and the parapet wall height is 1 m. In all cases, the street canyons are formed by two 4-story buildings, with a floor height of 3 m. The height and depth of the buildings are 12 m and the distance in between is 12 m (aspect ratio H/W = 1). Two continuous line-like sources of tracer gas are embedded in the street at ground level parallel to the canyon axis. The distance between the center of the source and the building façade is 3.5 m and the width of each source is 1 m (see Fig. 5b and Fig. 5b).

The upwind domain distance (Ud), the downwind domain distance (Dd), the domain height (Hd) and domain width (Wd) are 10H, 10H, 8.5H and 6.7H (Fig. 5a), respectively, where H is the building height. These dimensions are in line with the recommendations for LES simulations of generic long street canyons [49]. Block-structured grids are generated for the four cases using the surface-grid extrusion technique [52,53]. Fig. 6 shows the computational grid for case BWL. The grid consists of three blocks (Ω1, Ω2 and Ω3). The grid refinement ratio between each adjacent block is 1:2, following the recommendations provided in Ref. [54]. Block Ω1 uses cubic cells (Δx = Δy = Δz = H/96, i.e., 8 cells are applied along the depth of the balcony). Block Ω2 refers to the domain inside the street canyon, extending from the ground to the roof height. Block Ω3 consists of cubic cells (Δx = Δy = Δz = H/48), extended up to a distance of H out of the building surfaces. Block Ω3 consists of hexahedral cells with stretching ratios below 1.05. The grid resolution is determined based on a grid-sensitivity study (detailed in Section 3.6).

3.3. Boundary conditions

The long street canyons are simulated as spanwise homogeneous 3D geometries. At the inlet plane, neutral ABL approach-flow profiles of mean wind speed (U, Eq. (3)), turbulent kinetic energy (k, Eq. (4)) and turbulence dissipation rate (ε, Eq. (5)) are imposed [55], where z0 = 0.03 m is the aerodynamic roughness length, u*ABL = 0.3 m/s is the ABL friction velocity, κ = 0.41 is the von Karman constant, Cμ = 0.09 is the empirical constant, and Uref = 4.28 m/s is the wind speed at the roof height.

\[ U(z) = \frac{u_{ABL}^*}{k} \ln \left( \frac{z + z_0}{z_0} \right) \]  

\[ k(z) = \frac{\left( \frac{u_{ABL}^*}{k} \right)^3}{\sqrt{C_f}} \]  

\[ \epsilon(z) = \frac{u_{ABL}^*}{k(z + z_0)} \]  

To generate the fluctuations of the inflow profile, the vortex method [56] is employed. This method has been successfully used in previous LES validation studies by the authors for wind flows in the built environment [15,18,57]. In the present simulations, the number of vortices Nvor is 3720, obtained from Nvor = Nin/4 where Nin is the number of cells at the inlet plane [58]. This is based on the assumption that at least 2 cells are required in each direction to form a vortex. Periodic boundary conditions are used at the lateral domain sides (Fig. 5a). A constant static gauge pressure of 0 Pa is used at the outlet plane. The upper boundary of the domain is set as a slip wall, which implies that the normal velocity component and the normal gradients of all variables at this boundary are zero. Tracer gas SF6 that represents the vehicular exhausts is discharged from the two continuous line-like sources with the total emission rate per unit length (Q/l) of 10 g s⁻¹ m⁻¹.

3.4. Turbulence and dispersion modeling

The isothermal LES simulations are conducted with the WALE SGS model with constant Cref = 0.325 [44]. This SGS model has been successfully used in both validations presented in Section 2.1 and Section 2.2 and in previous studies for pollutant dispersion in the built environment [59,60]. The instantaneous pollutant concentration is treated as a scalar whose transport is described by an Eulerian advection-diffusion equation. The time-averaged (mean) convective mass flux Qci is defined as follows:

\[ Q_{ci} = \left\langle U_i c_i \right\rangle \]  

where i indicates the coordinate (u, v, w), the angle brackets denote the time averaging operator and the overbar denotes the filtering operation. The total mean turbulent mass flux Qci, is in LES is defined as follows:

\[ Q_{ci} = \left\langle u_i' c_i' \right\rangle + \left\langle q_{SGS,i} \right\rangle \]  

where u_i’ and c_i’ are the fluctuating components of velocity and concentration and q_{SGS,i} is the modeled SGS mass flux representing the effect of the unresolved small-scale eddies on the larger-scale dispersion. The instantaneous SGS mass flux is assumed proportional to the gradient of

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Fig. 4. Schematic of four cases (vertical center plane): (a) street canyon without balconies, (b) street canyon with balconies at both windward and leeward façades, (c) street canyon with balconies only at windward façade, and (d) street canyon with balconies only at leeward façade.
Building and Environment 212 (2022) 108746

5

resolved concentration:

\[ q_{\text{SGS}} = \pi \tau - \nu = -D_{\text{SGS}} \frac{\partial c}{\partial x_i} \]  

(8)

where \( c \) is the instantaneous SF6 concentration, \( u_i \) represents the instantaneous velocity components and \( D_{\text{SGS}} \) is the SGS mass diffusivity that links the SGS Schmidt number (\( Sc_{\text{SGS}} \)) and the SGS viscosity (\( \nu_{\text{SGS}} \)):

\[ Sc_{\text{SGS}} = \frac{\nu_{\text{SGS}}}{D_{\text{SGS}}} \]  

(9)

The turbulent Schmidt number \( Sc_t \) is taken equal to 0.7, as recommended by Refs. [44,61,85].

3.5. Numerical procedure

The solver settings are similar to those used in the validation studies. The LES simulations are initialized with solutions from 3D steady RANS simulations. For the RANS simulations, the realizable \( k-\varepsilon \) turbulence model [63] is used. For the LES simulations of the four cases, the time step \( \Delta t \) is set to be 0.012 s. The maximum Courant-Friedrichs-Lewy (CFL) number ranges from 0.91 to 1.04, which occurs in a small area above the canyon. Ahead of the data sampling, the LES simulations run for an initialization period of 640 s, i.e., about 10 flow-through times (\( T_{\text{ft}} = L/U_{\text{ref}} \), where \( L \) is the total streamwise domain length). This period allows removing the dependence on the non-physical initial state. After this initialization period, the data are sampled and averaged for 2560 s (about 40 \( T_{\text{ft}} \)).

All simulations are conducted on the Dutch national supercomputer Cartesius (SURFsara). Three nodes consisting of 32 Intel Xeon CPU E5-2697A v4 2.6 GHz cores are used for each simulation. The CPU clock time is about 4 s per time step. The total simulation time is about two weeks for each case.

3.6. Grid-sensitivity study

A detailed grid-sensitivity study is conducted for case BWL. A coarse, basic and fine grid (shown in Fig. 7) are generated in which 6, 8 and 10 cells are applied along the depth of the balcony, respectively. The total numbers of cells are 5.93 million, 13.84 million and 25.51 million, respectively. Time steps of 0.018, 0.012 and 0.0095 s are set for these grids of case BWL, ensuring the maximum CFL number to be lower than 1.

Fig. 8 displays the profiles of the \( C^+ \) from the three grids along 5 vertical lines in the street canyon: \( x/H = 0.04, 0.25, 0.50, 0.75 \) and 0.96. Note that in LES with implicit filtering, as used here, the local filter width equals the computational cell size. Therefore, strictly, a grid-independent solution cannot be achieved [64]. It appears that the \( C^+ \) obtained by the coarse grid is significantly lower than that by the basic and fine grids (Fig. 8). Compared to the basic grid, the average absolute differences of the coarse grid and fine grid are 0.96 and 0.40,
respectively. The relatively small differences between the basic and fine grids do not appear to justify the large increase in the computational time by the fine grid. Therefore, the resolution of the basic grid is retained for all the simulations.

4. Results

The following target parameters are evaluated:

- Mean wind velocity and mean concentration field:

The dimensionless mean velocity magnitude \((U/U_{ref})\) is defined as the local mean wind velocity magnitude divided by the “undisturbed” mean approach-flow wind speed at building roof height \(U_{ref} (= 4.28 \text{ m/s})\). The mean concentrations are expressed in the dimensionless form \((C^+\)] using Eq. (2), where \(H\) is the building roof height (12 m) and \(Q/l (= 10 \text{ g s}^{-1} \text{ m}^{-1})\) is the SF \(_6\) emission rate per unit length.

- Mean mass flux:

Since the street canyons are simulated as spanwise homogeneous 3D geometries, all the pollutants are released at the bottom and dispersed through the top horizontal surface of the canyon. Therefore, the vertical dimensionless mean convective mass flux \(Q_{c,z}/Q_0\) and turbulent mass flux \(Q_{t,z}/Q_0\) of the tracer gas are systematically investigated. The reference mass flux \(Q_0\) (g m\(^{-2}\) s\(^{-1}\)) is given by:
\[
Q_0 = (Q/l)/H
\] (10)

- Mean pollutant exchange velocity:

The dimensionless mean pollutant exchange velocity \((U_e/U_{ref})\) is a direct indicator for the actual exchange rate of the pollutants between the street canyon and the overlying atmosphere. The definition of \(U_e\) (m/s) follows Refs. [65,66] and is composed of the convective part (the first term on the right-hand side of Eq. (11)) and the turbulent part (second term on the right-hand side of Eq. (11)):
\[
U_e = U_e,c + U_e,t = \frac{\int Q_{c,z}dA}{A[C]} + \frac{\int Q_{t,z}dA}{A[C]}
\] (11)

where the numerators denote the pollutant fluxes across the exchange surface \(A\) (m\(^2\)), i.e., the mean vertical convective \(Q_{c,z}\) and turbulent mass fluxes \(Q_{t,z}\) through the top boundary surface \((z/H = 1)\) of the canyon. \([C]\) is the spatially-averaged pollutant concentration (g/m\(^3\)) over the control volume, i.e., the volume of the entire street canyon extending up to the roof height.

4.1 Mean wind velocity and mean concentration field

Fig. 9a-l shows the distributions of the mean velocity vector field and contours of \(U/U_{ref}\) in the vertical center plane. Fig. 9m–p displays the \(C^+\) distributions in the same plane for the four cases.

For the case without balconies (NB), the wind flow is directed downwards along the windward façade and is slightly decelerated towards the street surface (Fig. 9f). A primary recirculation vortex is
formed between the two buildings, with the core at a height of about 0.78H (Fig. 9a). Relatively high pollutant concentrations are observed near the street level at the leeward side and near the pollutant sources. This is in line with previous studies on pollutant dispersion in 1:1 long street canyons [67,68].

For the case with balconies at both windward and leeward façades (case BWL), the incoming wind flow separates at the roof above the windward balcony at level 4 and is directed downwards, leading to two small counter-rotating vortices on each balcony space at the windward façade: a counter-clockwise vortex at the higher half and a clockwise vortex at the lower half (Fig. 9h). The flow also separates at the lower edge of the lowest balcony, i.e. the one at level 2. Consequently, a secondary vortex forms at the street level (level 1) close to the windward corner due to the presence of this balcony. The core of the primary recirculation is located at the height of 0.83H, which is higher than case NB (Fig. 9b). For the leeward side, the upward flow induces a counter-clockwise vortex on each balcony space (Fig. 9g). The area-weighted average mean velocity within the canyon (below the roof height) in the vertical center plane is 54% lower than case NB. Fig. 9n indicates that higher $C^+$ values appear especially in regions near the leeward side of the canyon. The balconies obstruct the canyon flow and also act as compartments that yield nearly constant concentration within the balcony spaces. The area-weighted average dimensionless mean concentration ($C^+_{avg}$) within the canyon in the vertical center plane is 106% higher than case NB.

For the case with balconies only at the windward façade (case BW), the incoming airflow also separates at the roof at level 4 (Fig. 9j). The vortices on the balcony spaces and in the windward corner separate. Consequently, a secondary vortex forms at the street level (level 1) close to the windward corner due to the presence of this balcony. The core of the primary recirculation is located at the height of 0.83H, which is higher than case NB (Fig. 9b). For the leeward side, the upward flow induces a counter-clockwise vortex on each balcony space (Fig. 9g). The area-weighted average mean velocity within the canyon (below the roof height) in the vertical center plane is 54% lower than case NB. Fig. 9n indicates that higher $C^+$ values appear especially in regions near the leeward side of the canyon. The balconies obstruct the canyon flow and also act as compartments that yield nearly constant concentration within the balcony spaces. The area-weighted average dimensionless mean concentration ($C^+_{avg}$) within the canyon in the vertical center plane is 106% higher than case NB.

For the case with balconies only at the windward façade (case BW), the incoming airflow also separates at the roof at level 4 (Fig. 9j). The vortices on the balcony spaces and in the windward corner separate.
street level are similar to those in case BWL. The core of the primary recirculation is located at a height of about 0.92H (Fig. 9c). The area-weighted average mean velocity within the canyon in the vertical center plane of case BW is 51% lower than case NB. Similar to case BWL, pollutants accumulate near the leeward side and the ground (Fig. 9o). The $C_{\text{avg}}^+$ within case BW in the vertical center plane is 80% higher than case NB. The results of the aforementioned cases indicate that every street canyon with balconies at the windward façade has a much lower mean velocity and higher $C_{\text{avg}}^+$ than case NB. It can be concluded that the presence of windward balconies strongly resists the airflow from penetrating strongly and deeply into the canyon, resulting in a much lower wind speed at the street level and higher pollutant concentrations.

For the case with balconies only at the leeward façade (case BL), the flow field in the downstream half of the canyon is similar to case NB. The core of the primary recirculation vortex is located at a height of about 0.65H (Fig. 9d). The interaction between the upward flow and balconies at the leeward façade leads to a counter-clockwise vortex on these balcony spaces (Fig. 9k), which is similar to case BWL. However, for the region outside the balcony spaces near the leeward façade, the wind velocity is much higher than case BWL. The area-weighted average mean velocity within the canyon in the vertical center plane is only 21% lower than case NB. Fig. 9p indicates that pollutants accumulate in the leeward corner near the ground, with a concentration slightly higher than case NB. The $C_{\text{avg}}^+$ within the canyon in the vertical center plane is only 28% higher than case NB.

To investigate the pollutant concentration in the area where residents and pedestrians may be present, eight zones in the vertical center plane inside the canyon are considered, i.e. four at the windward side and four at the leeward side (see Fig. 10): (i) street sidewalk space (S1); (ii) balcony space on level 2 (B2); (iii) balcony space on level 3 (B3), and (iv) balcony space on level 4 (B4). Note that the width of the street sidewalk space is considered to be 2.5 m, which is in line with a typical sidewalk that allows four adults to walk comfortably next to each other [69]. Fig. 10a and b displays the $C_{\text{avg}}^+$ for these zones in the leeward side and windward side, respectively. Note that the results of the zones where no balcony is present are also displayed in the figure. It can be seen that for all cases, the concentration decreases with increasing elevation. In addition, higher concentrations are observed for zones at the leeward side than at the windward side. The following observations are made for the zones at the leeward side (Fig. 10a):

- For zone S1, the highest $C_{\text{avg}}^+$ is observed for case BWL, which is 94% higher than that for case NB. It is followed by case BW and case BL with about 61% and 21% higher $C_{\text{avg}}^+$ than case NB.
- For zones B2, B3 and B4, the highest $C_{\text{avg}}^+$ is observed for case BW, although balconies do not present. This is followed by case BWL, case BL and case NB. It is interesting to note that in these leeward zones of case BW, the $C_{\text{avg}}^+$ is even higher than case BWL. A possible reason is that the leeward balconies and their parapet walls in case BWL act as barriers to the entering of pollutants into these zones. For example, for zone B2 in case BWL, the pollutant released from the ground reaches the height of 4 m first, and then disperses into the balcony space (zone B2). While for case BW, zone B2 is directly exposed to the source. The pollutant released from the ground enters this zone directly when it reaches the height of 3 m.

For the zones at the windward side (Fig. 10b), the following observations are made:

- For zone S1, the $C_{\text{avg}}^+$ of cases BW, BWL and BL is 211%, 202% and 21% higher than that for case NB, respectively. These rather high pollutant concentrations in zone S1 of cases BW and BWL can be attributed to the counter-clockwise vortex inside this zone, which exacerbates the accumulation of pollutants (see Fig. 9j and h).
- For zones B2, B3 and B4, case BWL has the highest $C_{\text{avg}}^+$, followed by case BW, case BL and case NB.

### 4.2. Mean mass fluxes and mean pollutant exchange velocity

In LES simulations of the highly turbulent pollutant dispersion in the built environment, the proportion of the turbulent mass fluxes modeled by the SGS model to the total turbulent mass fluxes is usually negligible.
Fig. 11 shows the ratio of the mean vertical SGS mass flux to the total mean vertical turbulent mass flux (|Q_{SGS,z}/Q_{t,z}|) in the vertical center plane. The analysis is performed only for case BWL because the grid resolutions of the four cases are identical. This ratio is smaller than 0.01 in a large part of the canyon. An exception is the area near the ground level near the leeward façade, where the ratio is mostly smaller than 0.1.

Fig. 12 displays the distribution of the dimensionless mean vertical convective (Q_{c,z}/Q_0) and vertical turbulent (Q_{t,z}/Q_0) mass fluxes in the vertical center plane for the four cases. Overall, the convective fluxes are much larger than the turbulent fluxes, up to a factor of 8. The convective fluxes occur mainly near the windward and leeward façades. The turbulent fluxes occur throughout most of the canyon volume with two clear maxima near the top of the leeward façade and near the windward pollutant source. The following observations can be made for the four cases:

- **Case NB (Fig. 12a and e):** Q_{c,z} dominates the vertical pollutant exchanges within the largest part of the canyon. A high positive Q_{c,z}/Q_0 with a value up to 1.56 is observed near the leeward façade and a negative Q_{c,z}/Q_0 with a value down to −0.60 is observed near the windward façade. This implies that fresh air with low pollutant concentration is convected into the street canyon along the windward side, while the highly polluted air is convected upwards and partly out of the canyon along the leeward side. Concerning the turbulent mass fluxes, high positive values of Q_{t,z}/Q_0 occur close to the windward pollutant source and also above the roof level of the leeward façade (see Fig. 12e). This is in line with an observation of a long street canyon in Ref. [68]. Negative Q_{t,z}/Q_0 values occur in a small area near the leeward façade. Note that the isolines of C+ in Fig. 12e indicate negative vertical gradients of concentration in this region. This implies that the vertical turbulent mass fluxes are directed from a low-concentration region to a high-concentration region, i.e., the so-called CG mechanism [71]. The region with CG mechanism observed here is consistent with a past study on a cubic enclosure ventilated by a wall jet, in which the CG area is observed at the bottom leeward corner [14].

- **Case BWL (Fig. 12b and f):** Compared to case NB, the absolute values of Q_{c,z}/Q_0 of case BWL are substantially smaller (Fig. 12b). The maximum and minimum Q_{c,z}/Q_0 near the leeward and windward façades of the canyon are 1.24 and 0.56, respectively, the absolute value of which is 21% and 7% lower than in case NB, respectively. This is attributed to the obstruction of the flow within the canyon due to the presence of the balconies (see Fig. 9). The CG mechanism is observed in a small area near the leeward façade and in the windward street sidewalk space (Fig. 12f).

- **Case BW (Fig. 12c and g):** Also here the absolute values of Q_{c,z}/Q_0 of case BW are substantially smaller than case NB (Fig. 12c). The maximum and minimum values of Q_{c,z}/Q_0 are 1.31 and 0.51, respectively, the absolute value of which is 16% and 15% lower than in case NB. Compared to other cases, higher positive values of Q_{t,z}/Q_0 are observed in a large part of the canyon, including the area close to the leeward façade.

- **Case BL (Fig. 12d and h):** A relatively large positive Q_{c,z}/Q_0 is found near the leeward façade, and large negative values near the windward façade, which contribute considerably to the pollutant removal. The maximum and minimum values of Q_{c,z}/Q_0 are 1.41 and −0.54, respectively, the absolute value of which is 10% and 10% lower compared to case NB. Fig. 12h shows a pattern resembling that
Fig. 13a and b shows the area-weighted average dimensionless mean vertical outflow and inflow mass fluxes at the top boundary surface ($z/H = 1$) of the four canyon cases. It can be observed that case NB has the largest mean inflow and outflow mass fluxes, followed by cases BL, BW and BWL. The largest component in the outflow mass flux is the convective component, while the inflow mean turbulent mass fluxes are always zero for all the cases.

Fig. 13c presents the mean pollutant exchange velocity ($U_{e}/U_{\text{ref}}$). The highest total $U_{e}/U_{\text{ref}}$ of 0.083 is observed for case NB, while this number is 0.052, 0.044 and 0.037 for case BL, BW and BWL, respectively, i.e. 37%, 46% and 54% smaller than that for case NB. The $U_{e}/U_{\text{ref}}$ is displayed in two parts: the convective part ($U_{e,c}/U_{\text{ref}}$, obtained from the first term on the right-hand side of Eq. (11)) and the turbulent part ($U_{e,t}/U_{\text{ref}}$, obtained from the second term on the right-hand side of Eq. (11)). The relative importance of mean convective and turbulent mass fluxes as pollutant removal mechanism depends on the presence and location of balconies. The ratio of convective contribution to the total pollutant exchange velocity is 68% for case NB. This ratio reduces to 65%, 65% and 47% for case BW, case BL and case BWL, respectively. It can be concluded that the presence of balconies at both façades can strongly reduce the $U_{e}$ mainly by decreasing the inflow and outflow convective mass fluxes.

5. Discussion

The focus of the present study is on long street canyons with an aspect ratio (H/W) of 1. The results represent the flow and pollutant dispersion in the region where the canyon vortex is dominating the flow pattern. This implies long street canyons with L/H $\geq 7$. In real cities, street canyons can be short and the flow field near the lateral ends of the canyon is then the result of the superposition of the corner eddy and the canyon vortex, which render the flow pattern much more 3-dimensional and complex [20,72]. Future studies can evaluate the impact of the vertical and horizontal façade geometrical details. As a change in aspect ratio will impact the wind flow pattern in the canyon [73], future work can extend the present study towards other aspect ratios. It is expected that large differences in conclusions compared to the present study will only emerge when the aspect ratio of the long street canyon becomes so larger that the skimming flow regime is abandoned and the interaction flow regime sets in [74].

Balconies with 1 m depth and 1 m parapet wall are evaluated in this study. Previous studies have demonstrated that the balcony dimensions can affect the wind flow around isolated buildings [75,76]. Thus, the impacts of balcony dimensions for street canyons are therefore identified as a topic for further research. Recent studies have shown that building surface roughness details can strongly modify the near-building flow structures [77-81]. This study focuses on balconies as one of the most common façade details. Other forms of building surface roughness details can be evaluated in the future.

This study focuses on the perpendicular wind direction. Previous studies have shown that street-level pollutant concentrations significantly depend on the wind direction [82-84]. The impact of balconies on street canyons under other wind directions can be evaluated in the future.

6. Conclusions

This paper presents a systematic evaluation of the impact of balconies on the wind flow and pollutant dispersion in long street canyons with an aspect ratio of 1. The large-eddy simulation (LES) approach, validated with wind-tunnel measurements, is employed. The main conclusions of this study are:

The presence of building balconies can strongly modify the wind flow pattern within street canyons, especially for balconies at the windward façade. The presence of windward balconies prevents the airflow from penetrating deep into the canyon, resulting in low wind speed inside the canyon and therefore also at the street level. Compared to the case without balconies (case NB), the area-weighted average mean velocity in the vertical center plane within the canyons with balconies at both windward and leeward façades (case BWL), balconies at the windward façade (case BW), and balconies at the leeward façade (case BL) are reduced by 54%, 51% and 21%, respectively. The area-weighted average dimensionless mean concentration ($C_{\text{avg}}^{+}$) in the same plane for cases BWL, BW, and BL are 106%, 80% and 28% higher than case NB, respectively. The presence of windward balconies (case BWL and case BW) can strongly increase the pollutant exposure for pedestrians, while the presence of balconies at the leeward façade (case BL) has less impact on the pollutant concentration.

The rate of pollutant removal from street canyons, expressed by the dimensionless mean pollutant exchange velocity ($U_{e}/U_{\text{ref}}$), is strongly reduced by the presence of balconies. The $U_{e}/U_{\text{ref}}$ of case BL, case BW and case BWL is 54%, 46% and 37% smaller than that of case NB,

![Fig. 13. Area-weighted average (a) outflow and (b) inflow dimensionless mean vertical convective mass flux ($Q_{c,c}/Q_{0}$) and mean turbulent mass flux ($Q_{c,t}/Q_{0}$) and (c) dimensionless mean pollutant-exchange velocity ($U_{e,c}/U_{\text{ref}}$) at the top boundary surface of the canyon for four cases, displaying in convective ($U_{e,c}/U_{\text{ref}}$) and turbulent parts ($U_{e,t}/U_{\text{ref}}$).](image-url)
respectively. The relative importance of mean convective and turbulent mass fluxes as pollutant removal mechanisms depends on the presence and location of balconies. The results indicate that the presence of balconies has a crucial influence on the pollutant transport mechanism. The ratio of convective contribution to the total pollutant exchange velocity is 68% for case NB. This ratio decreases to 65%, 65% and 47% for case BW, case BL and case BWL, respectively.

The results above also suggest that in studies of urban ventilation and outdoor air quality, the presence of façade geometrical details need to be taken into account to avoid the overestimation of wind velocity and understimation of pollutant concentrations within urban street canyons.

CRediT authorship contribution statement

Xing Zheng: Writing – original draft, Investigation, Data curation, Conceptualization. Hamid Montazeri: Writing – review & editing, Supervision. Bert Blocken: Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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