On the Mechanism of Air Pollutant Removal in Two-Dimensional Idealized Street Canyons: a Large-Eddy Simulation Approach

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LES for Pollutant Removel in Idealised Street Canyons 1

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Abstract Flow resistance, ventilation, and pollutant removal for idealized two-dimensional (2D) street canyons of different building-height to street-width (aspect) ratios AR are examined using the friction factor f, air exchange rate (ACH), and pollutant exchange rate (PCH), respectively, calculated by large-eddy simulation (LES). The flows are basically classified into three characteristic regimes, namely isolated roughness, wake interference, and skimming flow, as functions of the aspect ratios. The LES results are validated by various experimental and numerical datasets available in the literature. The friction factor increases with decreasing aspect ratio and reaches a peak at $AR = 0.1$ in the isolated roughness regime and decreases thereafter. As with the friction factor, the ACH increases with decreasing aspect ratio in the wake interference and skimming flow regimes, signifying the improved aged air removal for a wider street canyon. The PCH exhibits a behaviour different from its ACH counterpart in the range of aspect ratios

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tested. Pollutants are most effectively removed from the street canyon with AR = 0.5. However, a minimum of PCH is found nearby at $AR = 0.3$, at which the pollutant removal is sharply weakened. Besides, the ACH and PCH are partitioned into the mean and turbulent components to compare their relative contributions. In line with our earlier Reynolds-averaged Navier-Stokes calculations (Liu et al. 2011), the current LES shows that the turbulent components contribute more to both ACH and PCH, consistently demonstrating the importance of atmospheric turbulence in the ventilation and pollutant removal for urban areas.

Keywords: Air quality, City ventilation, Large-eddy simulation, Pollutant removal, Urban areas.

1 Introduction

In view of the growth of urbanization and population in the current era, urban air quality has been an important research topic for years (Britter and Hanna 2003; Vardoulakis et al. 2003; Ahmad et al. 2005). Apart from three-dimensional (3D) cubes (Coceal et al. 2006; Kanda 2006), a street canyon is the basic unit constructing a city, and a fundamental understanding of the transport processes within the street canyon, helps elucidate the ventilation, as well as promote pollutant removal from the ground to the urban boundary layer (UBL) above (Liu and Barth 2002).

Because of the similarity of heat and mass transport, hot ribs have been employed to study the forced heat transfer over rough surfaces. Chow (1959) introduced k-type and d-type flows to characterize the flow over repeated ribs placed in a cross flow. Analogously, idealized two-dimensional (2D) street canyons are commonly used in urban climate research. Their building-height to street-width (aspect) ratio AR is the key parameter defining the building geometry and the flow patterns. Oke (1988) characterized the flows in street canyons into three regimes, namely isolated roughness ($AR < 0.3$, wide street), wake interference ($0.3 \leq AR \leq 0.7$), and skimming flow ($0.7 < AR$, tall buildings). It is found that k-type flows are distinguished by flow re-attachment and separation between the ribs. These flow characteristics are in line with the prevailing entrainment of air in the isolated roughness regime (Jiménez 2004). Similar to d-type flows, a dividing streamline bridges the top of leeward and windward ribs in which the recirculating flows are isolated from the flow aloft in the skimming flow regime (Belcher 2005). Bottema (1997) proposed the correlation between roughness and transport processes but this was difficult to quantify. These flow characteristics explain the retention and re-entrainment of pollutants in 2D street canyons in the wake interference regime (Liu et al. 2011).

The urban climate community is increasingly interested in the skimming flow regime because of the closely packed nature of buildings in a city. A series of studies have been performed in the Department of Mechanical Engineering, the University of Hong Kong to examine the ground-level air quality as a function of street-canyon geometry. The concept of air exchange rate (ACH) and pollutant exchange rate (PCH) was proposed by Liu et al. (2005) to quantify the air quality in street canyons using large-eddy simulation (LES). While LES is computationally more demanding, Li et al. (2005) later used the renormalisation group (RNG) k-ϵ turbulence model to formulate the ACH for Reynolds-averaged Navier-

Stokes (RANS) applications. Recently, Cheng et al. (2008) extended the RANS formulation to calculate PCH. These studies have presented two simple indicators measuring the performance of ventilation and pollutant removal for idealized 2D street canyons in various configurations, such as high-rise buildings (Li et al. 2009) or in unstable thermal stratification (Cheng and Liu 2011*b*).

One of the major merits of ACH and PCH is the partitioning of transport processes into their mean and turbulent components. Applying LES to street canyons with unity aspect ratio in the skimming flow regime, Cheng and Liu (2011*a*) demonstrated that both ventilation and pollutant removal are largely governed by intermittency. On the other hand, a comprehensive RANS k-ϵ turbulence modelling study was conducted by Liu et al. (2011) in which the ACH and PCH for a wide range of aspect ratio were calculated to cover all the flow regimes. The most interesting finding is the dissimilar behaviours of ACH and PCH as functions of aspect ratio, suggesting the necessity of using both indicators simultaneously to measure ground-level ventilation and air quality. Apart from the dominant turbulent pollutant removal from street canyons to the UBL, pollutant re-entrainment, which drives roof-level pollutants downwards into the street canyon, was revealed. The RANS results showed that the pollutant re-entrainment is governed by the persistent entrainment of air via mean PCH, resulting in the prolonged pollutant retention.

The pollutant removal mechanism for idealized 2D street canyons has been primarily formulated after the aforementioned studies. However, the weaknesses of RANS k-ϵ turbulence models, handling flow separation, re-attachment, and re-circulation, might affect the modelling accuracy of transport processes. Previous

LESs have often overlooked the processes in isolated roughness and wake interference regimes because of the major concern of compact buildings in urban areas (Cui et al. 2004; Letzel et al. 2008; Gu et al. 2011; Michioka et al. 2011). Moreover, the roof-level intermittent transport processes calculated by RANS k-ϵ turbulence models could be prone to error under strong anisotropic shear. This study is thus conceived, using the more sophisticated LES, to investigate the ventilation and pollutant removal in all flow regimes for idealized 2D street canyons. In particular, we attempt to demystify the mechanism of pollutant re-entrainment, which is signified by a negative mean PCH, by calculating the transient, large-energy-carrying scales explicitly.

Our core objective is to contrast the characteristic ventilation and pollutant removal in idealized 2D street canyons with different aspect ratios ($0.0667 \leq AR \leq 2$) covering the three major flow regimes. Further to the RANS results of Liu et al. (2011), the mean and turbulent ACH and PCH calculated by the current LES are analyzed to elucidate the role of atmospheric turbulence in pollutant removal from urban areas. Finally, as a pilot trial, the correlation among ACH, PCH, and the friction factor is investigated to determine whether the flow resistance over hypothetical urban areas could serve as an appropriate indicator of city ventilation and pollutant removal.

2 Methodology

Computational fluid dynamics (CFD) is employed to calculate the wind and pollutant transport in idealized 2D street canyons of various aspect ratios. The LES with the one-equation subgrid-scale (SGS) model of the open-source CFD code OpenFOAM 1.6 (OpenFOAM 2012) is used. The mathematical model and the governing equations are detailed below.

2.1 Governing Equations

The incompressible Navier-Stokes equations in isothermal conditions are employed, which consist of the continuity equation

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

and the momentum conservation equation

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

Here, $\overline{u}_i$ are the resolved-scale velocity tensors in the i-directions, x_i are the Cartesian coordinates, ΔP_x is the background pressure gradient in streamwise direction, δ_{ij} is the Kronecker delta, and ν is the kinematic viscosity. The modified resolved-scale pressure is

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

where $\overline{p}$ is the resolved-scale kinematic pressure and k_{SGS} is the SGS turbulent kinetic energy (TKE). The SGS Reynolds stresses $-\tau_{ij}$ $(= -\left[\overline{u_i u}_j - \overline{u}_i\overline{u}_j\right]$) are modelled in the form

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

using the Smagorinsky SGS model (Smagorinsky 1963). Here, ν_{SGS} $(= \mathrm{C}_k k_{SGS}^{1/2} \Delta)$ is the SGS kinematic viscosity, Δ $(= [\Delta_x \Delta_y \Delta_z]^{1/3})$ is the filter width, and C_k (=

0.07) is an empirical modelling constant. The mass conservation is calculated by the advection-diffusion equation for a passive and inert pollutant

$$\frac{\partial \overline{\phi}}{\partial t} + \overline{u}_i \frac{\partial \overline{\phi}}{\partial x_i} = \kappa \frac{\partial^2 \overline{\phi}}{\partial x_i \partial x_i} - \frac{\partial \sigma_i}{\partial x_i} \quad (5)$$

where $\overline{\phi}$ is the resolved-scale pollutant concentration and κ is the mass diffusivity. Analogous to Reynolds stresses, the SGS pollutant fluxes σ_i $(= [\overline{\phi u_i} - \overline{\phi}\overline{u}_i])$ are modelled by gradient diffusion

$$\sigma_i = -\kappa_{SGS} \frac{\partial \overline{\phi}}{\partial x_i} \quad (6)$$

where κ_{SGS} $(= \nu_{SGS}/Sc)$ is the SGS mass diffusivity and Sc $(= 0.72)$ is the Schmidt number.

2.2 Computational Domain and Boundary Conditions

A 3D computational domain of height $6h$ is used for the LES (Fig. 1). As with Cai et al. (2008), the spatial domain consists of a pair of hypothetical leeward and windward buildings of equal height h, and an open channel of depth $5h$. An idealized unit of a 2D street canyon is constructed by extending the open channel by $h/2$ horizontally over both the upstream and downstream buildings. Given a constant building height h, the street width b between the leeward and windward buildings is the sole parameter controlling the aspect ratios. The computational domain is of size $5h$ in the homogeneous spanwise direction (with the same building geometry) in which the properties are averaged to calculate the ensemble average in the analysis. The flow aloft, which is driven by the pressure gradient ΔP_x in the open channel, is aligned perpendicular to the street axis, representing the worst scenario for pollutant removal. The infinitely long and infinitely repeating street canyons are simulated using cyclic boundaries in the horizontal directions. No-slip conditions ($\overline{u}_i = 0$) are applied to the solid boundaries, while the domain top is assumed to be shear free ($\partial\overline{u}/\partial z = \partial\overline{v}/\partial z = \overline{w} = 0$). All the solid boundaries, including the leeward and windward facades, building tops, and streets, are prescribed at a uniform pollutant concentration Φ. Unlike the cyclic boundaries employed in the flow, a zero-pollutant inflow and an open-boundary condition are applied at the upstream inflow and downstream outflow, respectively. In the spanwise direction, the pollutant boundary condition is assumed to be cyclic similar to its flow counterpart.

2.3 Numerical Method

In the current LES, the implicit second-order accurate backward differencing is used in the time integration. The second-order accurate Gaussian finite volume method (FVM) is adopted to calculate the gradient, divergence, and Laplacian terms. The spatial domain is discretized into different numbers of elements (6.5 $\times 10^6$ to 8 $\times 10^6$) depending on the aspect ratio. The first element is placed at around five wall units measured from the nearby solid boundary to resolve the near-wall flows. The Reynolds number Re ($= \overline{U}h/\nu$) based on the mean flow speed $\overline{U}$ (calculated by the average value in the vertical direction) and the building height is in the range of 1.10×10^5 to 1.27×10^5, which is high enough for flows to be independent of molecular viscosity.

3 Results and Discussion

We focus on the relation between the aerodynamic resistance, and the rates of ventilation and pollutant removal along the opening gap of street canyons. Their behaviour in different flow regimes is discussed in this section. In the analysis, angular parentheses $\langle\cdot\rangle$ represent the ensemble-averaged LES properties in the temporal domain and the homogeneous spanwise direction. Instead of the velocity scale, the friction factor f is used to describe the kinematic effects, while the ACH and PCH are used to measure the ventilation and the pollutant removal, respectively. It is noteworthy that several other indicators, such as the exponential decay time constant (Lee and Park 1994), the integral dilution time scale (Sini et al. 2005), the pollutant transfer coefficient (Barlow and Belcher 2002), the pollutant exchange velocity (Bentham and Britter 2003), the wall transfer velocity (Narita 2007), the purging flow rate, the visitation frequency, and the residence time (Bady et al. 2008), are also commonly used to measure the air quality in a street canyon.

3.1 Friction Factor

The Darcy-Weisbach equation (Munson et al. 2009) depicts the head loss due to the skin friction along a given length of pipe as a function of flow properties. The loss in kinematic pressure Δp can be expressed as a function of the channel length L, mean flow speed $\overline{U}$, friction factor f, and hydraulic diameter D_h $(= 2WH/(W+H))$ for a rectangular channel of width W and height H, as follows

$$\Delta p = f\left(\frac{L}{D_h}\right)\left(\frac{\overline{U}^2}{2}\right). \tag{7}$$

Re-ordering Eq. 7 yields

$$f = \frac{\Delta p D_h / L}{\left(\overline{U}^2/2\right)} = \frac{\tau_w}{\left(\rho \overline{U}^2/2\right)} \ , \tag{8}$$

so that the friction factor f can be defined as the ratio of the shear stress τ_w ($= \rho \Delta p D_h / L$, where ρ is the fluid density) to the mean kinetic energy per unit volume. It also represents the pressure difference required to sustain a flow against the flow resistance.

Figure 2a shows the LES friction factor calculated by Eq. 8. The shear stress is calculated by the force balance in the UBL $\tau_w = \rho \Delta P_x \times 5h$. Also shown are the measurements (Han 1984) and the RANS k-ϵ turbulence model results (Liu et al. 2011). Han (1984) measured the flow resistance over 2D ribs placed in a cross flow in a rectangular channel. The current LES overpredicts slightly compared with the measurements in the isolated roughness regime, which could be due to the different methods used to measure the pressure difference across the test section. In the wake interference and part of the skimming flow regimes, the trend of the modelling results is consistent with each other, although the experimental measurements of Han (1984) did not extend to high aspect ratios. The laboratory measurements and modelling results collectively suggest that the friction factor peaks at around $AR = 0.125$ and decreases thereafter with decreasing aspect ratio.

In the isolated roughness regime, the LES shows that the friction factor decreases nearly monotonically with decreasing aspect ratio, i.e., the wider the street, the lower is the flow resistance. The flows are characterized by the persistent air entrainment down to ground level and the subsequent flow separation on the windward side. The decreasing resistance is attributed to the wider building separation and the smaller shear drag over the smooth ground surface (compared to the form drag due to the impingement on the building facades), resulting in the reduced overall flow resistance across a basic unit of street canyon.

Further reducing the street width switches the flow from the isolated roughness to the wake interference regimes in which the friction factor decreases with increasing aspect ratio. Different from the flow in the isolated roughness regime, the prevailing air masses do not touch down on the ground surface. The flow only partly entrains into the upper street canyon, and the ground-level separation diminishes instead. A direct flow impingement is observed on the windward facade that in turn increases the form drag and the friction factor of the street canyon unit as well.

In the skimming flow regime, the upper part of the street canyon is too narrow for persistent entrainment of flow aloft. The impingement on the windward facade does not exist so the LES-calculated friction factor decreases as a result of domination of the weaker shear drag. The aspect ratio of the LES is limited to one. On the other hand, the k-ϵ turbulence modelling results of Liu et al. (2011) show a more uniform friction factor for narrow street canyons. More detailed studies are therefore necessary to examine the flow structure and the resistance for street canyons with $AR > 1$ in order to elucidate the aforementioned difference between LES and k-ϵ turbulence model.

It is worth noting the different behaviours of the friction factor calculated by the k-ϵ turbulence model of Liu et al. (2011) and the current LES in the skimming flow regimes of higher aspect ratio. The friction factor calculated by the k-ϵ turbulence model converges to around $0.01 \leq f \leq 0.02$. Its LES counterpart, however, is reduced to a lower value that does not show an asymptotic behaviour. This dissimilarity could be a result of the single-length-scale assumption in the k-ϵ turbulence model such that the small-scale intermittent entrainment/de-entrainment is not calculated accurately. Besides, a 2D spatial domain is employed in the k-ϵ turbulence model while a 3D domain is used in the LES. The 3D turbulent motions may lead to different normal stresses that in turn deviate significantly from the idealized 2D motions. The modelling accuracy of the k-ϵ turbulence model and LES has been compared in detail elsewhere (Tominaga and Stathopoulos 2010; Liu and Chung 2012).

3.2 Air Exchange Rate

Ventilation of street canyons is determined from the air exchange rate (ACH), which was introduced by Li et al. (2005) and Liu et al. (2005) using a k-ϵ turbulence model and LES, respectively. The ACH is calculated by integrating the upward air velocity normal to the roof level, i.e., it measures the overall volumetric air removal through the opening gap of a street canyon. A higher ACH thus favours ventilation, carrying aged air from the street canyons to the UBL. For an idealized 2D street canyon, the total ACH ($ACH = \overline{ACH} + ACH''$) is partitioned into its mean

$$\overline{ACH} = \int_{roof} \langle \overline{w}_+ \rangle \, dA \tag{9}$$

and turbulent

$$ACH'' = \int_{roof} \langle w''_+ \rangle \, dA \tag{10}$$

components. Here, the subscript + signifies that only the upward velocity component is considered and A is the opening gap area of the street canyon. The mean ACH, $\overline{ACH}$, represents the upward volumetric airflow rate driven by the persistent mean flows. Analogously, the turbulent ACH, ACH'', carries the aged air upward by the intermittent (upward) turbulent flow. In Fig. 2b, ACH, $\overline{ACH}$, and ACH" exhibit a similar pattern for the range of aspect ratio tested, i.e., the ACH decreases with decreasing aspect ratio in the isolated roughness regime, but decreases with increasing aspect ratio in the wake interference and skimming flow regimes. A broad peak of ACH is observed in the range of $0.0667 \leq AR \leq 0.125$. A wider (narrower) street has a lower (higher) aspect ratio, and thus it is ventilated more (less) efficiently.

In the isolated roughness regimes, as discussed previously, the prevailing air masses entrain down to the ground level. The aged air masses are thus purged away from the ground level on the windward side by advection (Liu and Chung 2012). A wider street canyon is therefore more favorable for entrainment that in turn improves the ACH. In the skimming flow regime, a primary recirculation is developed inside the street canyon that is isolated from the flow aloft. A dividing streamline (Belcher 2005), bridging the leeward and windward buildings, reduces the persistent entrainment/de-entrainment. The recirculating flow in the street canyon and the flow aloft in the UBL are decoupled, which is similar to the flow over a smooth surface. The ACH is thus largely governed by the intermittent turbulent component ACH'', leading to a lower level of air exchange. In the wake interference regime, although recirculations persist in the street canyons, they are not isolated from the UBL. The fresh air aloft entrains only the upper part of the street canyons (Cheng et al. 2008). The shallow entrainment, because of its limited vertical and horizontal extents, carries less aged air away from the street canyons by advection. Nonetheless, the air exchange by purging (aged air removal by advection) is more efficient than turbulent transport. Hence, the ACH in the wake interference regime is in-between those of isolated roughness and skimming flow regimes.

Taken together, the results observed in the three regimes for the range of aspect ratios tested, clearly show that the ventilation in an idealized 2D street canyon is dominated by turbulent transport. The contribution from $\overline{ACH}$ to the total ACH is rather limited (10% to 20%), we therefore should further examine the role of atmospheric turbulence in the ventilation of urban areas. Cities are mostly compact in design, thus, the roof-level turbulence mainly governs the ventilation performance of street canyons, contributing up to 80% to 90% to the total ACH (in wake interference and skimming flow regimes). Apart from the mean wind, increasing the level of atmospheric turbulence over a city helps remove the ground-level aged air from street canyons in an effective manner.

3.3 Pollutant Exchange Rate

Similar to its ACH counterpart, the pollutant exchange rate (PCH) is calculated by LES to evaluate the pollutant removal performance of an idealized 2D street canyon. It measures the net amount of total pollutants being removed per unit time from the street canyon to the UBL. Hence, the higher the PCH, the more pollutants can be removed, implying an improved ground-level air quality. Analogous to ACH, the total PCH ($PCH = \overline{PCH} + PCH''$) is comprised of the mean

$$\overline{PCH} = \int_{roof} \langle \bar{w} \rangle \langle \bar{\phi} \rangle \, dA \tag{11}$$

and the turbulent

$$PCH'' = \int_{roof} \langle w'' \phi'' \rangle \, dA \tag{12}$$

components, which are calculated from the vertical pollutant fluxes.

Figure 2c depicts the normalized PCH of 2D idealized street canyons as a function of aspect ratios. Different from its ACH counterpart, because of the unequal pollutant concentrations across the opening gap of the street canyon, PCHs can be positive (upward) or negative (downward) that is clearly illustrated in Fig. 2c. Positive and negative PCHs measure the pollutant removal and re-entrainment, respectively.

In the isolated roughness regime, the PCH is quite uniform for the range of aspect ratios tested. In view of the persistent entrainment of fresh air from the UBL down to the street surface, most of the ground-level pollutant, following the aged air masses, is purged away from the street canyon by the prevailing wind in the streamwise direction. Therefore, the mean PCH contributes almost 50% to the total PCH, which is largest among the three flow regimes tested.

In the wake interference regime, the PCH behaves differently from its ACH counterpart. A minimum of total PCH ($= 0.0015\overline{U}\Phi A$) is clearly observed at $AR = 0.3$, suggesting a substantial drop in pollutant removal in the wake interference regime for idealized 2D street canyons. The degraded PCH is caused by the shallow entrainment of prevailing air which is unable to touch down the ground level to purge the pollutants away from the street canyons to the UBL by advection.

Instead, the entrainment of air carries roof-level pollutants, which are originated from the ground level, downwards into the street canyon. The persistent downwards pollutant flux, which is illustrated by the negative $\overline{PCH}$ (Fig. 2c), weakens the net (upward) pollutant removal that eventually prolongs the pollutant retention, resulting in the reduced total PCH in the wake interference regime.

The PCH decreases with increasing aspect ratio in the skimming flow regime. The mean PCH is negligible (or even negative) so the pollutant removal is dominated by the turbulent component PCH''. Besides, the narrow opening gap area between the leeward and windward buildings are connected by the dividing streamline. This isolated nature deters mean pollutant removal, leading to the decreasing total PCH.

3.4 Consistency with Other Studies

Also shown in Fig. 2 are the detailed k-ϵ turbulence model results of Liu et al. (2011). In particular, it provides data for narrow street canyons with aspect ratios up to 2.5 that complements the current LES findings.

The friction factors calculated by the k-ϵ turbulence model and the current LES agree well with each other in the range of aspect ratios tested except in the skimming flow regime of high aspect ratios (Fig. 2a). The reasons are detailed previously in Section 3.1.

Similar to the friction factor, the ACHs calculated by the k-ϵ turbulence model and the current LES show a discrepancy in the skimming flow regime (Fig. 2b). The LES-calculated turbulent components is lower than that of the k-ϵ turbulence model. Alike the friction factor calculation, this difference is caused by the inherent modelling weaknesses of k-ϵ turbulence models handling turbulent transport processes. This finding signifies the dissimilarities between k-ϵ turbulence model and LES, and the associated modelling errors. A similar difference is also found in the PCH in the skimming flow regime.

Additional data from literature are compared in Fig. 2c to examine the accuracy of the current LES. The consistent findings in PCHs from different studies, which are detailed in this section, collectively suggest the pollutant entrainment/de-entrainment mechanism formulated in the previous section.

Cai et al. (2008) used another LES model to examine the pollutant removal from street canyons in the skimming flow regime. The pollutant transfer coefficient, which is equivalent to the PCH adopted in this study, was used to compare the pollutant removal behaviours. Their results clearly demonstrated that, in line with our LES findings, the pollutant removal from a 2D idealized street canyon decreases with increasing aspect ratios. We believe that the reasons behind are similar to ours discussed in the previous sections.

Barlow and Belcher (2002) and Barlow et al. (2004) conducted naphthalene sublimation experiments over 2D idealized street canyon models in wind tunnels of different sizes. They focused on the pollutant removal behaviours in the skimming flow and wake interference regimes for a range of aspect ratios. In the skimming flow region, the data points are rather sparse that exhibit 20% to 25% of variation for a given aspect ratio. Nevertheless, they fall within the various modelling data sets that collectively suggests the weakened pollutant removal with increasing aspect ratio. Fewer data points were sampled in the wake interference regime, whereas, a mild drop in pollutant removal is observed in the transition across the wake interference and skimming flow regimes. This minimum pollutant exchange rate measured by wind tunnel experiments agrees well with our modelling results using both k-ϵ turbulence model and LES, showing the characteristic pollutant entrainment/de-entrainment for 2D idealized street canyons.

3.5 ACH and PCH as Functions of Friction Factor

Figure 3 expresses the total ACH ACH and the total PCH PCH as functions of the friction factor f in attempt to determine their correlation. In this preliminary trial, the urban roughness elements are identical in the form of idealized 2D street canyons, their roughness is only adjusted by the street-canyon aspect ratios. The total ACH, which is calculated by the k-ϵ turbulence model (Liu et al. 2011) and the current LES, consistently increases with increasing friction factor. Least square fitting of the data points shows that the correlation coefficients for k-ϵ turbulence model ($R^2 = 0.69$) and LES ($R^2 = 0.94$) are high. Hence, the friction factor could be adopted as a parameter to estimate the total ACH or ventilation of a street canyons. On the other hand, least square fitting of the total PCH is less correlated with the friction factor with $R^2 = 0.58$. In particular, the results from the k-ϵ turbulence model shows that the friction factor and PCH is essentially uncorrelated. It is likely caused by the pollutant entrainment/de-entrainment across the wake interface and skimming flow regimes. This loose correlation as a function of friction factor, similar to that revealed in Liu et al. (2011), also demonstrates the necessity of using ACH and PCH simultaneously to measure the ventilation and pollutant removal of a street canyon.

4 Conclusions

The large-eddy simulation (LES) with the one-equation subgrid-scale (SGS) model is applied to calculate the wind and pollutant transport in idealized two-dimensional (2D) street canyons with aspect ratios $AR = 0.0667$ and 0.0909 in the isolated roughness regime, 0.25 and 0.3333 in the wake interference regime, and 0.5, 0.6, 0.8, 1, and 2 in the skimming flow regime. The parameters, including the friction factor f, the air exchange rate (ACH), and the pollutant exchange rate (PCH) are determined to evaluate the drag, the ventilation and the pollutant removal. The friction factor attains its maximum value at $AR = 0.125$ due to the entrainment of air from the urban boundary layer (UBL) aloft to the street canyons. The ACH and PCH are compared with the k-ϵ turbulence modelling results of Liu et al. (2011) and consistent findings are obtained. The ACH decreases with increasing aspect ratio, illustrating the more efficient removal of aged air masses from a wider street canyon. However, the improved ventilation does not guarantee a more efficient pollutant removal. The minimum PCH appears in the wake interference regime that suggests the possibility of pollutant re-entrainment in 2D street canyons. Furthermore, the turbulent components of ACH and PCH are the key contributors, implying the importance of atmospheric turbulence in the improvement of city ventilation and street-level air quality. A preliminary study is attempted to examine the parametrizations of the total ACH and PCH using the friction factor. Modelling results show that the flow resistance of flows over street canyons is a potential reliable estimate of the total ACH but not the total PCH. Additional investigations are required to improve the PCH estimate.

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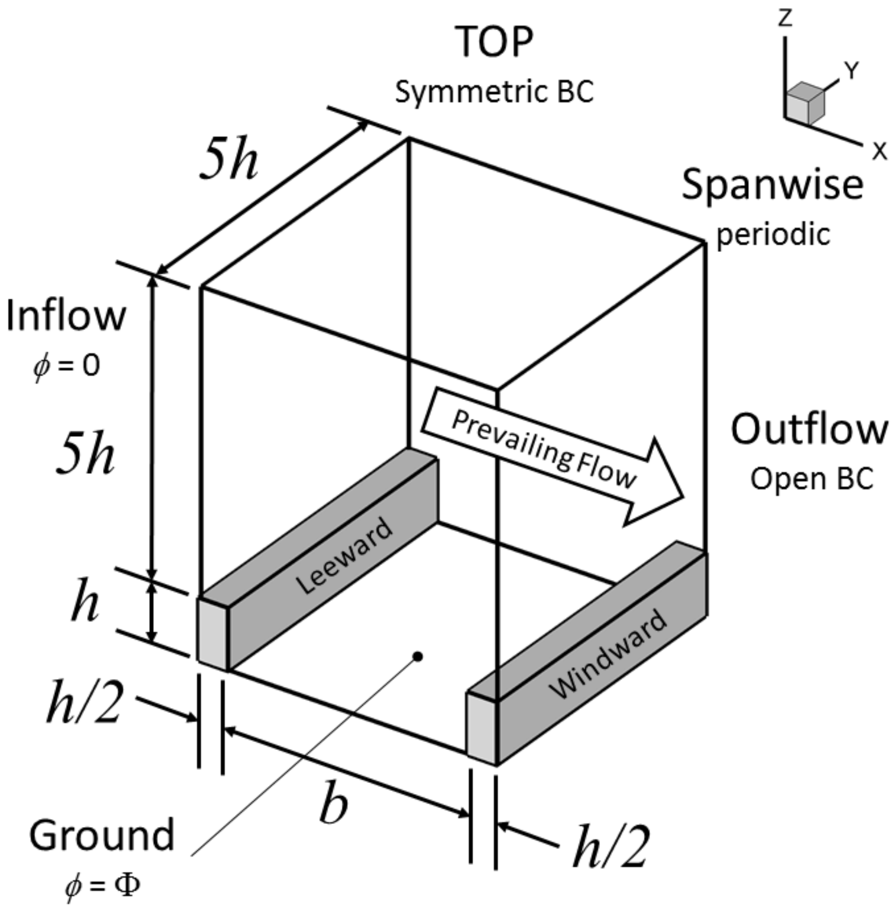

Fig. 1 Three-dimensional LES computational domain.

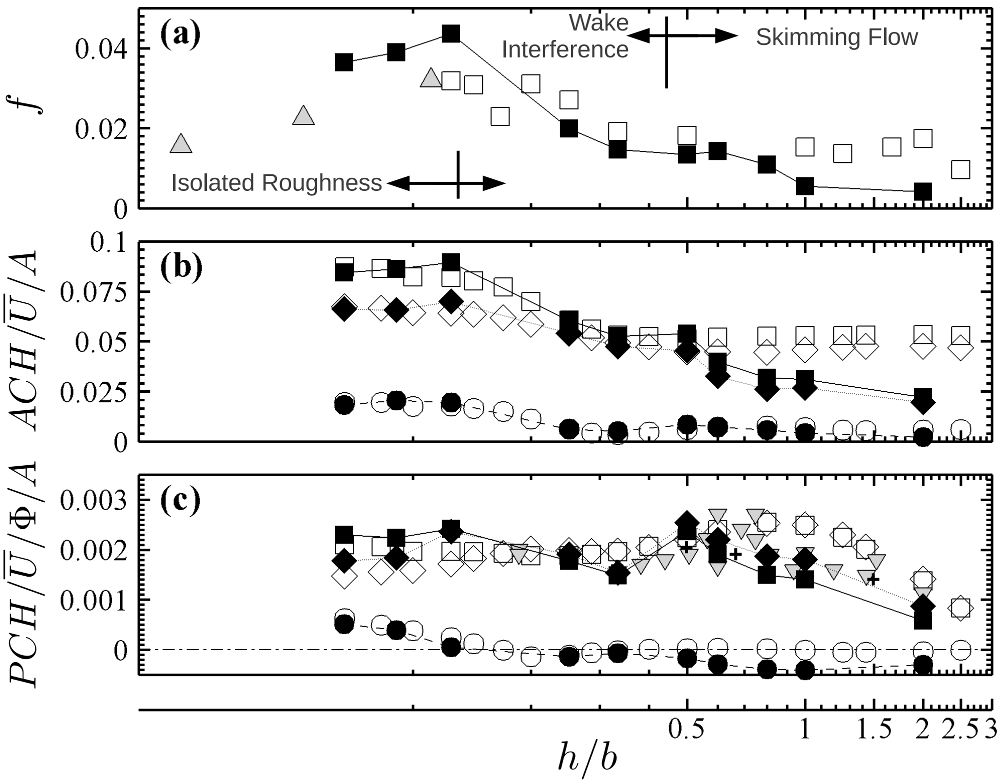

Fig. 2 (a). Friction factor f, (b). air exchange rate ACH, and (c). pollutant exchange rate PCH for idealized 2D street canyons of different building-height-to-street-width (aspect) ratio h/b calculated by k-ϵ turbulence model (empty symbols, Liu et al. 2011) and the current LES (filled symbols). ○: Mean component, ◇: turbulent component, and □: total quantity. Also shown in shaded symbols are the experimental and numerical data available in literature. Δ: friction factor measurements of Han (1984), ▽: naphthalene evaporation measurements of Barlow and Belcher (2002) and Barlow et al. (2004), and +: LES calculation of Cai et al. (2008). The dash-dotted line represents zero PCH. The flow regime is defined based on the current LES results instead of that stated in Oke (1988).

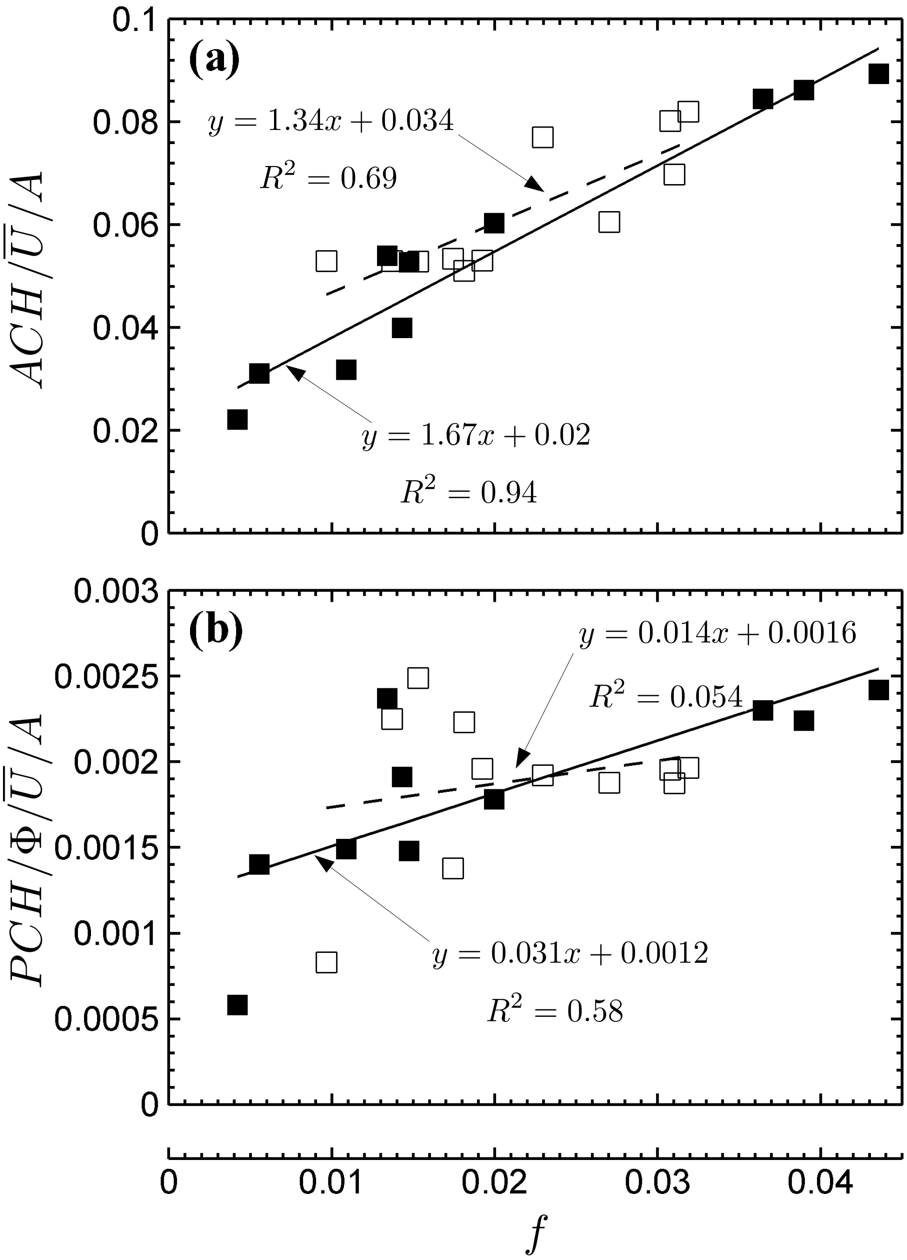

Fig. 3 (a). Air exchange rate ACH and (b). pollutant exchange rate PCH plotted as functions of friction factor f. Also shown are the linear regressions for the modelling results. ■ and ——: LES results, and □ and − − − − −−: k-ϵ turbulence model results.