Abstract: A large-eddy simulation (LES) is performed to study the flow and pollutant removal in two-dimensional (2D) idealized street canyons with building-height-to-street-width (aspect) ratio equal to unity. Different from the previous LESs, a larger computational domain is adopted that consists of three identical street canyons under the shear layer of thickness five times the building height \( h \). One of the objectives of this study is to determine the minimum size of computational domain required in order to accurately capture the turbulence inside the street canyons. The two-point correlations of the streamwise, spanwise, and vertical velocities are investigated, suggesting that the computational domain should be at least sized \( 2h \) in height and \( 6h \) in width for a reliable turbulence calculation inside the street canyons. In addition, the current LES profiles of vertical mean wind and turbulence are compared with other LESs available in literature, which adopted different domain sizes. The pollutant dispersion inside the street canyons is performed using uniform area pollutant sources on the streets. The pollutant removal is abundant at the roof-level windward corner. Employing the quadrant analysis of the vertical pollutant flux, it is found that sweeps is the dominating components for pollutant removal from the street canyons.

Key words: Urban street canyon; large-eddy simulation (LES); computational domain size; turbulent transport; pollutant removal;

INTRODUCTION
With the current extensive urbanization, 0.3% of the world land surface is covered by built-up area (World Bank 2005). Urban air pollution problems are thus commonly encountered in cities (Fenger 1999) adversely affecting the health of over 2 billion urban inhabitants (WHO 2000). By 2030, the urban development would grow rapidly by 2.5 times attaining 1.1% of the total land area (equal to 5% to 7% of the total arable land) with a total urban population about 4 billion (World Bank 2005). There is apparently a need for improving the urban air quality and city ventilation.

To reveal the fundamental pollutant removal mechanism in urban areas, the idealized street canyon geometry is commonly adopted (Belcher 2005). In particular, a vast effort has been devoted to elucidate the characteristics of flow and pollutant dispersion in two-dimensional (2D) street canyons. Utilizing the building-height-to-street-width (aspect) ratio \( h/b \), Oke (1988) classified the flow pattern into three regimes, namely skimming \( (h/b > 0.7) \), wake interference \( (0.3 < h/b < 0.7) \) and isolated roughness \( (h/b < 0.3) \). There are numerous experimental (Meroney et al. 1996; Kastner-Klein and Plate 1999; Barlow and Belcher 2002) and numerical (Vardoulakis et al. 2003; Li et al. 2006) studies focusing on street canyons of \( h/b = 1 \). The results consistently confirm the large, persistent recirculation inside and near the roof-level flow flapping of the street canyon (Louka 1998; Letzel et al. 2008). Traffic emissions are the utmost pollutants in urban areas, hence, pollutant sources are usually placed at the street level to examine the impact of vehicular exhaust. After emission, the pollutants are diluted by the primary recirculation inside the street canyon, then are removed to the free-stream air by the turbulence at the roof level.

In the past decade, computational fluid dynamics (CFD) has become a popular tool for street canyon studies. It enables the simulation of idealized conditions as well as the detailed records of the flow variables in a spatial-temporal manner, facilitating complete datasets of the flow and pollutant dispersion in street canyons. With the rising computer power, a number of large-eddy simulations (LESs, Liu and Barth 2002; Cui et al. 2004; Cai et al. 2008; Letzel et al. 2008; Li et al. 2008) have been performed so the turbulence structure inside a street canyon has been investigated in details. Moreover, statistical methods, such as conditional sampling and spectral analysis, have been conducted (Cui et al. 2004). In this study, instead of one single street canyon, three identical 2D street canyons of \( h/b = 1 \) are placed in a computational domain of size \( 6h \) (height) \( \times 6h \) (width). Our primary objectives are using LES to examine the effect of domain size on the turbulence characteristics inside and above street canyons, and to elucidate the mechanisms of pollutant removal and re-entrainment.

METHODOLOGY
The LES is carried out by the open-source CFD code OpenFOAM (OpenFOAM 2010). The resolved-scale transport equations of continuity, momentum, and pollutant (passive scalar) in incompressible flow are solved. The one-equation subgrid-scale (SGS) model (Schumann 1975) is used to model the SGS turbulence kinetic energy. The Spalding’s law of the wall (Spalding 1962) is applied for the near-wall treatment. The governing equations are discretized by the finite volume method (FVM) with second-order-accurate schemes in space and time.

The building height \( h \), building width \( w \), and street width \( b \) are the same in the current LES (Figure 1). Area pollutant sources with constant pollutant concentration \( C_a \) are prescribed on all the streets. A free-slip boundary condition is used at the upper boundary and no-slip boundary conditions are used for all the buildings and streets. Periodic boundaries for the flow are applied in the horizontal directions. Zero concentration and open boundary for pollutant are used at the inflow and the outflow, respectively, while a periodic condition is assumed in the spanwise direction. A constant pressure difference is prescribed in the free-stream layer \( (z/h > 1) \) to drive the free-stream flow. In this LES, the Reynolds number \( (Re) = 8000 \) and the Schmidt number \( (Sc) = 0.72 \) for the pollutant. The statistics are sampled for a time period of 40h/U0 with 500 intervals after 40h/U0 of turbulence activation time. The mesh sizes \((N_h, N_s, N_w)\) are \((50, 200, 50)\) for the street canyon and \((300, 200, 200)\) for the shear layer. The mesh is stretched towards the urban surface at the bottom. In the following discussion, the
resolved quantities are denoted by overlines and the resolved fluctuations are denoted by \( \cdot \). Spatial and temporal averaging are performed on the flow variables that are denoted by \( \langle \cdot \rangle \). All the flow statistics are averaged over the three street canyons.

**RESULTS AND DISCUSSIONS**

**Effect of LES domain height on the mean flow and turbulence**

The resolved-scale mean streamwise \( \langle \bar{u} \rangle \) and spanwise \( \langle \bar{v} \rangle \) velocities, and their standard deviations \( \sigma_u \) and \( \sigma_v \) are compared with previous LES studies (Liu et al. 2004; Li et al. 2008) in Figures 2 and 3. The vertical profiles at \( x/b = -0.25, 0 \) (centreline) and 0.25 of each studies are shown. Computational domains of different heights are employed in the studies.
The aim of this section is to investigate how the domain height affects the mean wind and turbulence within and above the street canyons. Using the free-stream wind speed \( U_f \) as the velocity scale, it is found that both the mean wind and turbulence are smaller in the current LES. In particular, the magnitude of the mean wind speed and turbulence in Liu et al. (2004) is the largest, followed by Li et al. (2008) and the current LES. Obviously, the variation is due to the different heights employed in the computational domains. A shorter domain height lowers down \( U_f \) that turns out overestimating the normalized quantities, suggesting that \( U_f \) may not be an appropriate characteristic velocity scale for street canyon studies with shallow domain (< 6h) as shown in the current LES. The mean winds inside the street canyon predicted by the three LESs agree with each other quite well. Above the street canyon, a more vigorous increase in \( u \) with increasing height is observed in Liu et al. (2004) over the other two LESs. Besides, \( u \) attains the free-stream speed just above the roof level of street canyon that could be caused by the limited shear layer thickness (0.5h) adopted in previous studies.

Table 3. Height of the computational domain in different studies.

<table>
<thead>
<tr>
<th>Studies</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>LES, one-equation (Current LES)</td>
<td>6h</td>
</tr>
<tr>
<td>LES, dynamic (Liu et al. 2004)</td>
<td>1.5h</td>
</tr>
<tr>
<td>LES, one equation (Li et al. 2008)</td>
<td>2h</td>
</tr>
</tbody>
</table>

In view of the large roof-level velocity gradient, sharp peaks of velocity fluctuations (\( \sigma_u \) and \( \sigma_v \)) are observed at the roof level of street canyon in Liu et al. (2004). Similar peaks are also found in Li et al. (2008) but with smaller magnitudes. In the current LES, the \( \sigma_u \) profile exhibits a mild roof-level peak but not the \( \sigma_v \) profile. The sharp peaks developed in the LES of Liu et al. (2004) and Li et al. (2008) are caused by the shallow computational domain enforcing zero-gradient flow at the upper boundary and the over-promoted roof-level turbulence. Inside the street canyon, the three sets of LES results agree reasonably well with each other. The small differences observed are believed to be the results of the variation of the characteristic velocity scales \( U_f \).

To determine the minimum size of the computational domain for street canyon required in LESs, the two-point correlations

\[
R_{uu} (r, r_{ref}) = \left[ \frac{\sigma_u (r) - \langle u_r \rangle}{\sigma_u (r_{ref})} \right] \left[ \frac{\sigma_u (r_{ref}) - \langle u_r \rangle}{\sigma_u (r_{ref})} \right]
\]

with \( \sigma = \sigma_u, \sigma_v \) and \( \sigma_w \), and \( (x_{ref}, z_{ref}) = (0, h) \) and \( (0, 2h) \) are calculated (Figure 4). For the two reference locations considered, the values of \( R_{uu} \) sustain for a longer width than do \( R_{vv} \) and \( R_{ww} \) especially in the streamwise direction. For the reference location at \( (0, h) \), which is the centre of the roof level of the street canyon, \( R_{uu} \) diminishes at a separation of \( h \) upstream, \( 3h \) downstream and \( 2h \) in the vertical direction. Therefore, the horizontal extent employed in the current LES is barely enough that \( R_{uu} \) drops to zero at \( x/b = -2 \). For \( R_{vv} \) and \( R_{ww} \), their spread is much smaller (about 0.5h) both in the horizontal and vertical directions. For another reference location \( (0, 2h) \), \( R_{uu}, R_{vv} \) and \( R_{ww} \) decay much slower in the horizontal and vertical directions compared with the case at a lower elevation. In particular, \( R_{uu} \) does not drop to zero horizontally across the whole domain, implying that the currently LES domain is not wide enough to capture the turbulence scales in the shear layer. The spread of \( R_{vv} \) and \( R_{ww} \) is smaller and is only \( h \) to \( 2h \).

As shown in the comparison of the LES results and the analyses of the two-point correlations, the computational domains for all the LESs are not long enough capturing accurately the turbulence in the shear layer. On the other hand, the mean wind and turbulence inside the street canyons in the LESs show consistent features, suggesting that the size of computational domain...
would not affect too much the transport processes below the roof level. The result of $R_{uu}$ at $(0, h)$ further demonstrates that the turbulent length scale at the roof level of street canyon is about $3h$ horizontally and $h$ vertically. Therefore, to accurately simulate the roof-level turbulence, a computational domain of at least $2h$ in height and $6h$ in width is necessary.

**Pollutant removal**

The pollutant inside the street canyons is carried by the primary recirculation and is removed from the street canyon mainly near the windward facade by turbulence. As shown in Figure 5a, the pollutant is quite well-mixed by the primary recirculation inside the street canyons. Regions of lower pollutant concentration are observed near the windward facades that are caused by the local, rapid turbulent pollutant removal. This region of low pollutant concentration is smaller in size for the street canyon farther downstream because of the re-entrainment of upstream pollutant. The standard deviation of pollutant concentration $\sigma_c$ depicts a peak at the roof level as a result of the local turbulence generation by wind shear (Figure 5b). The elevated $\sigma_c$ near the street level is due to the local, high pollutant concentration. In the centre core of the street canyon, $\sigma_c$ decreases as the street canyon locating more downstream. Analogously, this is believed to be to the result of the pollutant re-entrainment where the pollutant concentration is more uniform inside the street canyon (Figure 5a).

**Pollutant removal**

Adapting the quadrant analysis for shear stress $<u''w''>$ (Wallace et al. 1972; Lu and Willmarth 1973), the method of conditional sampling is applied to the vertical turbulent pollutant flux $<w''c''>$ to examine the pollutant removal and re-entrainment behaviours. $<w''c''>$ is divided into four quadrants (Table 2, Chen 1990; Katul et al. 1997; Katsouvas et al. 2007). Ejections and sweeps represent pollutant removal (Figures 6a and 6c, respectively), while inward and outward interactions represent pollutant re-entrainment (Figures 6b and 6d, respectively). As expected, ejections and sweeps are the dominating components since the pollutant is continuously removed from the street canyons to the shear layer. By the definition in Table 2, we may argue that, at the roof level, ejections represent the outgoing pollutant and sweeps represent the incoming of fresh air from the shear layer. At the roof level, the sweeps is slightly larger than the ejections, suggesting that the pollutant removal is mainly driven by the fresh air entrainment. Moreover, both the three street canyons show similar patterns of the four quadrants regardless of the street canyon positions. It seems that the pollutant re-entrainment affects the pollutant removal mechanism insignificantly.

**Table 2. Quadrants of vertical pollutant flux $\langle w''c'' \rangle$.**

<table>
<thead>
<tr>
<th>Quadrants</th>
<th>Ejections</th>
<th>Outward Interactions</th>
<th>Sweeps</th>
<th>Inward Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directions</td>
<td>$c'' &gt; 0, w'' &gt; 0$</td>
<td>$c'' &lt; 0, w'' &gt; 0$</td>
<td>$c'' &lt; 0, w'' &lt; 0$</td>
<td>$c'' &gt; 0, w'' &lt; 0$</td>
</tr>
</tbody>
</table>

**Figure 6. Quadrant analysis of vertical turbulent pollutant flux $\langle w''c'' \rangle$.** (a) Ejections; (b) Outward interactions; (c) Sweeps; (d) inward interactions.

**CONCLUSIONS**

A large-eddy simulation (LES) is performed to simulate the flow and pollutant dispersion in a two-dimensional (2D) idealized street canyon of aspect ratio equal to one. A comparatively larger computational domain, consisting of three street canyons and of domain height equal to $6h$, is adopted. To investigate the effect of domain height on the street canyon flow...
patterns, the current results are compared with the previous LES studies of Liu et al. (2004) and Li et al. (2008) which utilized domain heights of 2h and 1.5h respectively. Similar to Liu et al. (2004), sharp peaks of $\sigma_u$ and $\sigma_v$ are found at the street canyon roof which is due to the limited shear layer thickness. Inside the street canyon, the profiles of mean wind and turbulence exhibit similar patterns in all the three LESs. However, the use of $U_0$ to normalize the flow variables could be prone to error as the magnitudes of the normalized variables depend closely on the domain height employed. The effect of domain size is further examined by calculating the two-point correlations for the streamwise ($R_{uu}$), spanwise ($R_{vw}$) and vertical ($R_{ww}$) velocities with respect to the reference locations at the roof level (0, h) and the shear layer (0, 2h). It is revealed that $R_{uu}$ does not drop to zero when the reference location is in the shear layer, suggesting the horizontal extent employed currently is not large enough covering all the turbulence scales in the shear layer. However, from the results of reference location at the roof level, $R_{uu}$ drops to zero at about half-width of the computational domain. Hence, a domain with at least 2h in height and 6h in width is necessary to simulate the large-scale turbulence at the roof level of the street canyons.

Considering uniform area pollutant sources at streets, the pollutant distribution is found to be well-mixed inside the street canyon by the primary recirculation. Pollutant removal or fresh air entrainment occurs mostly at the upper windward corner. Using the quadrant analysis on the vertical pollutant flux, sweeps are found to be more important than ejections, implying the pollutant removal mechanism is mainly driven by fresh air entrainment.

REFERENCES
Letzel, M. O., Krance, M. and Raasch, S. 2008: High resolution urban large-eddy simulation studies from street canyon to neighbourhood scale, Atmos. Environ., 42, 8770-8784.
OpenFOAM 2010: http://www.opencfd.co.uk/openfoam/.